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WADC TECHNICAL REPORT 54-323
PART 2

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THE EFFECT OF SURFACE FINISHES ON FRICTION AND FUSION OF PARACHUTE CLOTH AND LINE

VASILIS LAVRAKAS
ADOLPH KATZ

LOWELL TECHNOLOGICAL INSTITUTE RESEARCH FOUNDATION

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WRIGHT AIR DEVELOPMENT CENTER

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OCTOBER 1955

MATERIALS LABORATORY
CONTRACT No. AF 18(600)-136
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WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
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WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared by the Lowell Technological Institute Research Foundation under U. S. Air Force Contract No. AF 18(600)-136. This contract was initiated under Project No. 7320, "Air Force Textile Materials", Task No. 73201, "Textile Materials for Parachutes", formerly RDO No. 612-12, "Textiles for High Speed Parachutes", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. Jack H. Ross acting as project engineer.

We would like to express our gratitude for the capable and wholehearted efforts of Mr. Harry Demas, a graduate student at the Institute, whose thesis work toward the Master's Degree contributed a major portion of the data presented in this report.

We would also like to thank the concerns who generously contributed to the various phases of this program. Their assistance and cooperation were sincerely appreciated.

The various lubricants studied in this program were evaluated only for their suitability in the special application of reducing frictional heat occurring between parachute cloth and cord. The results of this program do not indicate the possible effectiveness of the various lubricants when utilized for other lubrication applications.

This report covers the period of work from Jan 1952 to Dec 1954.

ABSTRACT

A belt friction apparatus was used to study the fusion of scoured parachute cloth and lubricated cord at high sliding speeds. Data obtained at speeds up to 97 ft/sec when extrapolated to higher speeds (100-140 ft/sec) indicate that no further significant data would be obtained regardless of the type of agent applied.

The effect of speed on fusion and friction has also been investigated. Primarily, three homologous series of high molecular weight organic compounds were used: high molecular weight fatty acids, alcohols, and monoesters. In their ability to prevent fusion, fatty acids were poorer than fatty alcohols, while fatty alcohols were poorer than fatty monoesters.

As the speed of rubbing increases, the resistance to fusion of lubricated nylon parachute materials decreases rapidly, and at high speeds (75 ft/sec) this resistance falls to alarmingly low levels.

The role of molecular weight in the phenomenon of fusion and lubrication was investigated and found to be an important factor. Other factors are undoubtedly present but were not investigated.

Anionic, cationic, and nonionic lubricants were also studied. As an insufficient number were investigated, no definite conclusions have been formulated.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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INTRODUCTION

The study of the effects of lubricants on the fusional and frictional properties of nylon parachute cloth and line has been motivated by an interest to minimize frictional damage to nylon parachute fabrics during deployment of the parachute. This damage occurs as a result of the frictional heat produced by the rubbing action when a parachute line slides over the canopy cloth at high speeds. The relatively low melting point of nylon (482°F) may be reached under these functional conditions of rubbing, leading in many instances to fusing of the fabric at the point of contact. Figure 1 is a photograph of the so-called "line burn" on nylon parachute fabric caused by fusion of the nylon under the severe frictional conditions often encountered in a parachute jump.

Since frictional heat can be lowered by reducing the coefficient of sliding friction, the use of lubricants as a possible remedial measure becomes apparent. The first phase in this program on the lubrication of parachute material was essentially utilitarian in nature.* It was of paramount importance at that time to devise an apparatus and a method by which a quick separation of lubricants effective in the prevention of fusion could be accomplished.

Further work, nevertheless, was needed to understand the basic phenomena of friction and the resulting fusion of parachute cloth when rubbed against the lubricated line.

If sufficient basic data were available, it would be possible to construct a suitable lubricant to better meet the requirements of parachute friction. In order to obtain information concerning such factors as the effect of rubbing speed on friction, and the physical and chemical requirements for a good lubricant, the following experimental programs were initiated:

1. A study of the effect of slack tension and speed upon friction and fusion between lubricated line and scoured canopy material.

2. A study of the effect of changing from a more polar (fatty acid) to a more non-polar (fatty ester) type of lubricant upon friction and fusion between lubricated nylon parachute materials.

3. A study of the effect of anionic, cationic, and nonionic lubricants upon friction and fusion between nylon parachute materials.

In view of these goals, the following basic studies were made:

1. Data obtained from tests at lower speeds were extrapolated to determine the effects of higher speeds upon friction and fusion.

* WADC TR 54-323, Part 1

2. It was possible to obtain some information (also using data obtained from the rapid separation of lubricants) as to the best possible type of chemical compound to be used in parachute lubrication. More generally, such a study may be of value in the selection and separation of present as well as future lubricants.

Pure chemical and a few commercial compounds were employed as lubricants for all of the tests. This made it possible to obtain valid data, and also to reach the high sliding speeds before fusion resulted.

APPARATUS AND PROCEDURE

The experimental studies were performed with the equipment described in WADC TR 54-323, Part 1* The principal element of the apparatus shown in Figures 2 and 3 is a revolving cast iron pulley (capable of revolving at speeds of 25, 36, 52, and 75 ft/sec), upon which is placed the test specimen of parachute cloth. The parachute cord is then wrapped over the cloth. The cord is attached at one end to a strain gauge while a known weight is suspended from the other end of the cord. The total force between the cord and cloth is measured by means of a strain gauge type load cell, and recorded upon a Brown "Electronik" potentiometer recorder. The frictional force is defined as the difference between the minimum force reading occurring during the sliding interval of 1.5 minutes and the known weight attached to the slack end of the cord. The coefficient of kinetic friction μ_k is calculated by means of the well known belt friction formula, $\frac{T_2}{T_1} = e^{\mu_k \theta}$, where $\underline{T_2}$ is the taut tension and $\underline{T_1}$ is the slack tension of the cord, and θ is the angle of wrap of the cord with the cloth on the pulley.

Five samples of lubricated cord were run against scoured cloth for each test. Only the cord was lubricated as this was the simpler and quicker procedure. Ambient conditions for testing were 65% RH and 70°F. If fusion did not occur after a running time of 1.5 minutes, the slack tension on the sample was progressively increased until fusion finally occurred. Fusing of the cloth and line was indicated by an abrupt increase in the frictional force registered on the recorder as well as by the ripping of the cloth. The maximum slack tension at the time of fusion is referred to throughout this report as the Fusion Load and serves as a measure of the effectiveness of a lubricant in preventing fusion.

The amount of lubricant present on the line was 10$\pm$ 1% of the conditioned weight of the line. Previous experience had indicated that the amount of lubricant must in general be greater than 5% to afford good protection against fusion. Ten per cent was therefore arbitrarily taken as a practical limit in the actual application of lubricant. It was also felt that this high percentage would tend to minimize variations in the test results caused by small differences of lubricant pickup between the different lines tested.

The experimental error in the friction force values was not always of a low order; however, the great mass of data generally resulted in coefficients of variation of less than 10%. The experimental error associated with fusion load data is not as clear cut as that associated with friction force. Nevertheless, certain trends are observed if the ranges in fusion load are plotted. From these trends, it is possible to arrive at conclusions concerning lubrication.**

* See Appendix A for details.
** For further details concerning testing procedure, see Appendix B.

SPECIMEN PREPARATION*

The preparation procedure of test samples was essentially the same as that followed in Part 1 of this report. The parachute materials used for all tests were:

1. Suspension Line Cord; Scoured nylon, Specification MIL-C-5040, Type III.

2. Parachute Cloth; Scoured nylon, Specification MIL-C-7020, Type I.

A statistical sampling of the nylon cloth and cord showed that, insofar as frictional forces and fusion were concerned, no significant differences existed when testing different sections of the cloth and line. Therefore, in all the work the cord and cloth were used as needed without employing special measures to ensure random sampling. It was also felt that because parachute cord and cloth are held to very close tolerances in their manufacture, it would not be necessary to continually test all lots of cord and cloth received for their conformance to specifications. Actually, the cloth used for the entire program was from a single production lot.

For this investigation, layers of fatty alcohols, esters, acids, and surface active agents were applied by simultaneously dipping five test lengths of cord into a solution of the lubricant for a period of ten minutes. The specimens were kept separate in the bath by means of a compartmented apparatus (Figure 4). The percentage pickup of the lubricant on the cord was determined by conditioning the lubricated samples for twenty-four hours and then weighing them. As the scoured cord had been conditioned and weighed before the lubricant was applied, the percentage pickup was found from the relation:

$$\text{Per Cent Pickup} = \frac{\text{Weight of Lubricated Line} - \text{Weight of Scoured Line}}{\text{Weight of Scoured Line}} \times 100$$

* For further details, see Appendix C, D, and E.

RESULTS AND DISCUSSION

The Effect of Slack Tension on the Coefficient of Sliding Friction

The relationship between slack tension and the coefficient of sliding friction at a fixed sliding speed of 25 and 75 ft/sec is presented in Figure 5. It is noted that as the slack tension increases the coefficient of sliding friction decreases and, unless fusion has occurred, approaches a constant value regardless of further increases in slack tension. This relationship occurred at various sliding speeds between 25 and 75 ft/sec. The decrease in the coefficient of friction at low loads is a deviation from Amontons' Law. From results obtained in metallic lubrication studies, Bowden and Tabor also report that at loads (less than 10 gm) Amontons' Law does not hold; but at higher loads the coefficient of friction is constant (1). The reason for this they say is ".......at these very small loads the deformation of the surface is insufficient to produce penetration of the lubricant film and we are measuring the interaction of the hydrocarbon film itself". At higher loads, however, penetration of the lubricant film almost invariably occurs and Amontons' Law is closely obeyed.

If the conclusions of Bowden and Tabor are valid, then, at low loads and under our test conditions, the bulk viscosity of the lubricant is a prime factor in the generation of frictional heat, while the nature of the fabric surfaces may be considered to be relatively unimportant. However, at the higher loads, where the penetration of the lubricant film occurs, both the nature of the fabric and the viscosity characteristics are important.

The Effect of Speed on Frictional Force

The relationships between speed and frictional force for several groups of lubricants at different slack tensions are plotted in Figures 6 to 10. Figures 6a, 7b, 8b, 9, and 10 contain incomplete data. The first four figures contain incomplete data because no further time was available to complete this study; the last figure is incomplete because the static frictional forces of these surface active agents were too irregular to obtain valid data.

For the fatty acids shown in Figure 6 the frictional force reaches a minimum value at about 36 ft/sec, and then increases as slack tension increases.

These same relationships between frictional force and speed are also observed, although to a lesser degree for the fatty alcohols (Figure 7) and esters (Figure 8).

Data obtained from lines lubricated with Polyethylene Glycol 400(Mono) Laurate* are plotted in Figure 9. Shroudlines which were lubricated with an emulsion of the compound in water show a steady decrease of frictional force with an increase in speed. However, the frictional force of lines lubricated with a solution of the same compound in ethanol is lower than in the case of water, and only begins to approach the values of the frictional force of lines lubricated from water emulsion at the higher speeds. This would indicate that the medium from which a compound was applied on the line has some effect on the frictional force. This difference is perhaps caused by a difference in distribution and penetration of lubricant, as a result of the different solvents used in applying the lubricant; or else,

* Glyco Products Co., Inc.

because of possible differences in moisture content of the lines attributable to differences in solvents. Although the lines were conditioned before testing, the moisture content of lines lubricated with the water emulsion might have been greater than those lines which were lubricated with a solution of the lubricant in alcohol. Previous work (1) has established the fact that frictional force is dependent upon the moisture content of the rubbing surfaces. At sufficiently high speeds, because of the higher temperatures produced, the moisture in the fabrics, it is assumed, will be vaporized. The curves of frictional force at high speeds should then begin to approach one another. From the general trend of the curves in Figure 9 there is evidence that this assumption is correct.

The relationship between kinetic frictional force and speed for the anionic (Arquad 2C and 2HT)* and cationic (**cationic compound A**) lubricants shown in Figure 10 also falls in line with that observed for other lubricants. However, it is not possible to say definitely if this is true as static frictional data were too erratic to be used.

The Effect of Speed on the Fusion Load

The work in this phase of the program was initiated to study the effect of speed on the fusion load for lubricated materials, and also to determine whether or not a study of lubrication at sliding velocities of 140 ft/sec would provide additional information beyond that obtained at 75 ft/sec. To accomplish this, high molecular weight fatty acids, alcohols, and esters were utilized as lubricants.

These compounds were selected both for their value as lubricants, as well as for the fact that they are commercially available as chemically pure agents. A check was made on the purity of these compounds by determining their melting and boiling points. As the values obtained did not differ from those given in the literature, no effort was made to purify these materials further.

Some time was also available for a brief study of a few anionic, cationic, and nonionic lubricants. A clear-cut view of the effect of speed upon the fusion load for parachute materials lubricated with surface active lubricants has resulted, and will be discussed in the following sections.

The average fusion loads as a function of speed for the fatty acids are presented in Figure 11. At low speeds the various fatty acid lubricants can readily be ranked for their effectiveness in preventing fusion. With increasing speed this distinction begins to disappear until at the higher speeds the fatty acids are approximately equivalent to each other in their effectiveness in preventing fusion as measured by their fusion loads. At 75 ft/sec the fusion load is approximately 60 grams, while at 25 ft/sec the fusion load varied for the different fatty acids at a range of approximately 350 to 500 grams. Thus, for a three-fold increase in speed the average fusion load has decreased approximately six to eight fold.

It was possible to run some tests for only a few lubricants at what is believed to be close to the maximum velocity, 97 ft/sec, obtainable from our apparatus. This was done for stearic acid, stearyl alcohol, and Polyethylene Glycol 400 (Mono) Laurate. However, as no other materials in a series were investigated, a definite statement cannot be made whether or not a separation in

* Armour Chemical Division

fusion loads between lubricants will be maintained at very high speeds.

Nevertheless, the general shapes of the curves in Figures 11-15 are interesting. They indicate that as the speed increases a sharp drop in fusion load occurs in the range from 25 to 52 ft/sec. With a further increase in sliding speed the curves tend to level off slightly but eventually will approach the velocity axis. This would indicate that for extremely high speeds fusion would occur regardless of any further reduction in slack tension. This is obvious since simple contact between two lubricated nylon bodies at extreme sliding speeds would generate sufficient heat to fuse the nylon. Thus, there is some critical speed above which no lubricant could be effective other than to delay fusion. Above this speed the lubricant would simply serve as a thermal insulator and delay the heat transfer to the nylon. The lubricating finish would have to be sufficiently thick so that the frictional heat would be generated within the lubricant itself.

These curves were generally extrapolated to a slack tension of 52 grams to obtain the speed at which the effectiveness of the lubricant in preventing fusion is believed to be poor. This speed is referred to as the limiting speed of the lubricant.

The limiting speed of fatty acids is found to be between approximately 78 and 90 ft/sec. These materials as lubricants are placed in Class II*; therefore, it is believed that an investigation of fusion and friction of Class II materials at higher speeds is not possible.

Another significant observation is that at 25 and 36 ft/sec a relatively low molecular weight fatty acid, n-capric acid, has the highest fusion load. This distinction is not maintained at speeds of 52 and 75 ft/sec; at these speeds all of the acids fall into approximately the same fusion load range (see Figure 11) No great difference exists between high molecular weight fatty acids at higher speeds as a result of their differences in molecular weight.

The fusion loads of the fatty alcohols as a function of speed are presented in Figure 12. The same type of curve observed in Figure 11 is also found for this case. There is little difference at low speeds between myristyl alcohol (C_{14}) and octadecanol (C_{18}) as lubricants. However, at higher speeds, 52 and 75 ft/sec, a separation between all compounds is present; i.e., octadecanol is better than myristyl alcohol, which in turn is better than dodecyl alcohol.

The highe molecular weight alcohols, C_{18} and C_{14} are the better lubricants at both the low and high speeds. At 75 ft/sec, the fusion loads of myristyl and octadecanol alcohols are separated by approximately 40 grams; myristyl alcohol would fall in Class II and octadecanol in Class III. The limiting speed is found to be approximately 87 ft/sec for dodecyl alcohol, 93 ft/sec for myristyl alcohol, and 103 ft/sec for octadecanol. This indicates again that for Class II and III lubricants it is probably not possible to investigate these materials at speeds higher than 103 ft/sec.

The fatty esters presented in Figure 13 also have the same type of curves associated with fusion load as a function of speed as the fatty acids and esters. The limiting speed for the fatty esters is found to be approximately 96 ft/sec for ethyl laurate, 112 ft/sec for ethyl myristate, and 134 ft/sec for ethyl stearate.

* For discussion of Classes see WADC TR 54-323, Part 1

The only lubricant which protects the nylon against fusion at 134 ft/sec is ethyl stearate, and this would only be true if the slack tension were in the neighborhood of 52 grams.

The nonionic agent, Polyethylene Glycol 400 (Mono) Laurate (Figure 14), shows the same general type of curve as the previous lubricants studied. The limiting speed, by extrapolation, is approximately 140 ft/sec. These results are summarized in Figure 21.

The anionic and cationic agents (Figure 15) are extremely poor lubricants as measured by the limiting speed. The results are as follows:

1. Arquad 2C (acetone and water solutions) - 33 ft/sec

2. Cationic Compound A (acetone solutions) - 36 ft/sec

3. Arquad 2HT (acetone solution) - 38 ft/sec

4. Arquad 2HT (water solution) and Cationic Compound A (water solution) - 40 ft/sec

The Coefficient of Kinetic Friction

In the original thinking, preparatory to experimentation, the coefficient of kinetic friction was considered as a possible measure of the effectiveness of a lubricant. A lubricant with a low coefficient of kinetic friction could be considered to be a better agent than one with a high coefficient of kinetic friction. If this were true, then the evaluation of lubricants might be accomplished by determining coefficients of kinetic friction.

Early in the program, however, it was soon realized that to establish the coefficient of kinetic friction as a criterion for the separation of lubricants would require an exorbitant amount of testing which would delay our program considerably. As a consequence, the fusion load was taken as a more satisfactory and realistic criterion for the following reasons:

1. The fusion load establishes the slack tension at which a lubricant fails at high speeds. There would be little doubt, once such a load was found, as to the effectiveness of a lubricant.

2. Almost as important as the first reason was the fact that the fusion load could be determined quickly, using only two test samples, in contrast to establishing the coefficient of friction as the criterion of lubrication which would have involved at least five or more samples.

However, it was desirable to determine whether or not a relation does exist between the fusion load and the coefficient of kinetic friction. Figure 16 compares the coefficient of kinetic friction (measured at a slack tension of 22 grams and a speed of 75 ft/sec) with the fusion load for the fatty acids, alcohols, and esters. A rough correlation exists between the fusion load for the fatty mono-esters and the coefficient of kinetic friction. The fatty alcohols, however, indicate an opposite trend from the fatty esters; i.e., as the coefficient of kinetic friction increases the effectiveness of the lubricant increases. Finally, for the fatty acids, fusion loads tend to remain constant although the coefficient of kinetic friction is increasing. Thus, no definite relation exists from one series of lubricants to the next between the coefficient of friction and fusion load.

It is of interest to note that the coefficient of kinetic friction for each lubricant maintains its relative position to all other lubricants as the slack tension increases at 75 ft/sec (see Figure 5b). Therefore, the lack of correlation would also apply at higher slack tensions.

Similar results to these have been reported in the investigations of Bowden and Tabor (2) for cholesterol and stearic acid films. Both materials have the same coefficient of friction but stearic acid does not wear off as rapidly as cholesterol, and, therefore, is the better lubricant.

The Effect of Molecular Weight of a Lubricant upon Friction

Figures 17 to 19 show the relationship which exists between the molecular weight of fatty acids, esters, and alcohols and the fusion load as speed is increased. The range (based on five samples) of fusion loads has been plotted rather than the average fusion points in order to provide a more comprehensive picture of the reproducibility of the fusion load data. If average fusion loads had been used in the graphs, the shape of the curves would change but slightly.

In Figure 17 for the fatty acids, at 25 ft/sec, an increase in the fusion load is observed between eight and ten carbon atoms, followed by a decrease between twelve and fourteen carbon atoms. In the range from fourteen to eighteen carbon atoms, the fusion load once again increases. This trend is duplicated at 36 ft/sec. However, at 52 and 75 ft/sec the curves no longer exhibit maxima and minima points; instead, they tend, after an initial increase, to level off.

The effect of increasing molecular weight upon fusion load for the parachute cords lubricated with fatty alcohols (Figure 18) indicates that at all speeds an increase in fusion load occurs when going from 12 to 14 carbon atoms. From 14 to 18 carbon atoms, at speeds of 25 and 36 ft/sec, the fusion load remains essentially constant; but at 52 and 75 ft/sec, octadecanol (C_{18}) appears to be a slightly better lubricant than myristyl alcohol (C_{14}).

The number of alcohols tested is not sufficient to give an accurate picture of the effect of increasing molecular weight upon fusion. Nevertheless, the results favor the view that alcohols with more than 12 carbon atoms are effective in protecting the nylon surfaces from fusing.

The fatty monoesters (Figure 19) show a definite increase in fusion load with an increase in molecular weight. Again the number of fatty esters tested is small, and does not furnish enough information to determine fully the behavior of the parachute cords lubricated with this class of compound. The type of curves obtained are remarkably similar to the fatty alcohols. Apparently, all that would be needed to obtain a highly effective lubricant would be to use a very high molecular weight ester; but this may not be so. For example, Spermaceti wax, which is primarily an ester of cetyl alcohol and palmitic acid, i.e., cetyl palmitate, $C_{15}H_{31}COOC_{16}H_{33}$, has a molecular weight of 480; whereas ethyl stearate, $C_{17}H_{35}COOC_2H_5$, has a molecular weight of 312. Spermaceti wax ought to be better by a factor of approximately 1.5 than the ethyl stearate. However, it was found from the experimental data of two samples that Spermaceti wax is only slightly better than ethyl stearate.

The curves for the fatty esters tend to level off at the high molecular weights. Consequently this trend, if it is a true one, would indicate that a limit exists in fusion load for increasing molecular weight, and that no significant protection against fusion would result if the molecular weight were increased beyond this point.

An examination of Figure 17 shows one other significant observation. Capric acid (C_{10}) which is more effective than the other fatty acids at low speeds (25 and 36 ft/sec) begins to lose its effectiveness, in comparison to other fatty acids, as the speed is increased. A flattening process occurs over the range of 25 to 75 ft/sec. Finally, at 75 ft/sec, the trend appears to favor the hypothesis that at high speeds the effectiveness of a lubricant varies with its molecular weight. These results are puzzling and would require more work to identify the factors involved. Other factors such as viscosity, vapor pressure, heat capacity, coefficient of thermal conductivity, and the presence or absence of hydrodynamic or boundary lubrication, which may affect the fusion load, are undoubtedly present. To unravel all of these possible factors requires further experimental and theoretical work.

The fusion loads for the series of normal fatty acids, alcohols, and esters at 75 ft/sec are compared in Figure 20. A clear-cut separation exists between the groups in their ability to prevent fusion. The fatty esters studied are best; the fatty alcohols are next best; while the poorest are the fatty acids. The curve for the fatty acids shows that with increasing molecular weight only a slight increase in protection against fusion results. For the fatty alcohols, a greater slope is associated with the curve. The slope of the fatty esters is the greatest of all. The C_{14} ester is about the same as the C_{14} alcohol; however, as molecular weight increases a separation occurs so that C_{18} ester (estimated from the ester curve) is better than C_{18} alcohol by approximately 55 grams.

The reason for such a separation of these types of compounds, though their molecular weights are alike, is not clear. Such results serve to emphasize that molecular weight is only one of several factors in the prevention of fusion. However, the trend of increasing resistance to fusion, at constant molecular weight, appears to show that as the nature of the compound shifts from a more polar to a more non-polar material, i.e., from fatty acids to fatty esters, the resistance to fusion also increases.

The Effect of Certain Commercial Cationic, Anionic, and Nonionic Lubricants Upon Fusion

To study further the effect of polarity upon the prevention of fusion, some commercial anionic, cationic, and nonionic agents were investigated. Figures 14 and 15 show the effect of speed on fusion load for these surface-active materials.

Cationic Compound A is a cationic agent with an approximate molecular weight of 584. It is a homologue of bis (2-ethyl hexyl) sodium sulfosuccinate,

$$\begin{array}{l} Na\,O_3\,SCHCOOR \\ \qquad\quad | \\ \qquad\; CH_2\,OOR \end{array}$$

The structure of "R" is $C_{13}H_{27}$ which is a mixture of branched chain isomers.

Arquad 2C and Arquad 2HT are both dialkyl dimethylammonium chlorides,

$$\left[\begin{array}{c} CH_3 \\ | \\ R - N - CH_3 \\ | \\ R \end{array}\right]^{+1} (Cl)^{-1}$$

with each R representing a long chain hydrocarbon derived from a fatty acid. These compounds are anionic surface active agents, with Arquad 2C having a molecular weight of approximately 260 and Arquad 2HT a molecular weight of approximately 324. Polyethylene Glycol 400 (Mono) Laurate is a nonionic surface active agent with a molecular weight of approximately 400.

Cationic Compound A with a molecular weight of about 584, which is a greater molecular weight than the molecular weight of Polyethylene Glycol 400 (Mono) Laurate, is definitely a less effective lubricant. On the other hand, the same result appears for Arquad 2C and 2HT which have lower molecular weights than the Polyethylene Glycol 400 (Mono) Laurate. Therefore, from the results presented in Figures 14 and 15, the nonionic lubricant is better than any of the ionic compounds.

No general conclusions can be drawn from these results. Additional experimentation must be done to determine more accurately the effect of ionic and nonionic compounds upon fusion. Nevertheless, because of the great difference in performance between ionic and nonionic compounds encountered in our previous testing program, polarity may be a factor in preventing fusion with a nonionic being better than an ionic lubricant, all other factors remaining constant.

SUMMARY OF RESULTS

A study has been made of the effect of speed as well as certain other factors upon the fusional resistance of lubricated nylon parachute materials. The resistance to fusion decreases very sharply with increasing speed, so that in the higher speed ranges the material can only withstand negligible loads before fusion occurs.

Of the chemically pure fatty acids, alcohols and esters studied, the esters are the better lubricants. The best fatty ester, ethyl stearate, has been found by extrapolation to offer some measure of protection against fusion even at speeds of 140 ft/sec.

Little additional information can be gained by investigating conditions at extreme speeds (140 ft/sec). Results indicate that fusional resistance is of a low order at these high speeds; and as the trends indicate a good separation between poor and good lubricants at all speeds, this separation may be assumed to hold at higher speeds than those studied.

The frictional force of lubricated materials generally decreases with increasing speed until a limiting velocity is reached. After this point the frictional force begins to increase.

The coefficient of kinetic friction always decreases as the slack tension is increased, leveling off at high slack tensions.

From a brief study of cationic, anionic, and nonionic lubricants, the nonionic appeared to be best. The results are inconclusive as an insufficient number of lubricants were investigated.

The coefficient of kinetic friction is not necessarily a suitable criterion for the effectiveness of a lubricant in preventing fusion. Molecular weight, however, is a prime factor in the effectiveness of a lubricant at high speeds. As molecular weight increases the fusion preventing ability of a lubricant also increases at all speeds, except for the fatty acids, which exhibit maxima and minima points in the fusion load curve as the molecular weight increases. At high speeds the differences between fatty acids are not great, and the over-all trend of fusion prevention increasing as molecular weight increases is once more observed.

Other factors than molecular weight may play an important role in the performance of a lubricant. Such factors as viscosity, vapor pressure, heat capacity, coefficient of thermal conductivity, and the presence or absence of hydrodynamic or boundary lubrication may be of importance. Further study is needed to establish the importance of these variables. In addition, from a physiochemical viewpoint, the change from a polar (fatty acid) to a non-polar substance (fatty ester) increases the effectiveness of the lubricant. This consideration may also enter into the question of the best type of parachute lubricant.

On a hypothetical basis, the ideal lubricant for protecting nylon parachute materials from fusion should be a compound of low vapor pressure, low viscosity, high molecular weight, non-polar or hydrophobic in nature, high heat-oxidative stability, resistant to mildewing, and, if surface active, nonionic. In addition, the compound should be distributed evenly on the surface of the material, and should firmly adhere to the surface. This "ideal" compound appears to be most closely approached in this work by high molecular weight fatty esters; however, further studies must be undertaken in the investigation of other types of compounds before any definite statement can be formulated.

APPENDIX A

DESCRIPTION OF THE APPARATUS

The apparatus (Figures 2 and 3) comprises a cast iron pulley A, five inches in diameter and two and one-half inches wide, with a slit cut across its width to accomodate the test fabric. A strip of parachute cloth is wrapped tightly around the pulley. The parachute cord F is attached to the strain gauge B, drawn around the frictionless pulley C, and wrapped around the pulley A to produce an angle of wrap of 360°. (The cord may also be adjusted by a suitable arrangement of the pulleys to produce an angle of wrap of 90°, 180°, or 270°.) The cord then passes over the frictionless pulley D, and a weight W is suspended from the end of the cord. The pulley A is attached to the drive shaft G which is motor driven. The pulley A can be driven at peripheral linear speeds of 24, 35, 52, and 75 ft/sec by means of a multiple pulley arrangement. The output of the strain gauge B is fed through an amplifier, and the resultant force recorded on a Brown "Electronik" potentiometer strip chart recorder. From this chart the sliding frictional force involved at any given time may be found.

APPENDIX B

TESTING PROCEDURE

The lubricated samples were suspended from the hooks of a drying bar for twenty-four hours in a conditioning room. After twenty-four hours, the end of the line which was suspended from the hook on the drying bar was attached to the strain gauge during the test. This procedure was always followed to eliminate or minimize the effect of any possible variation of the per cent pickup within the line. All tests were conducted at 70°F, 65% R.H., and with an angle of wrap (θ) of 360°.

A weight of 20 grams was suspended from the free end of the line for a total slack tension, T_1, of 22 grams; i.e., a 20 gram weight plus 2 grams, which is the weight of the line from the frictionless pulley, D, to the free end of the line from which the weight is suspended. The strain gauge was activated and the chart started. A slight twist was given to the shaft which rotated the pulley (A) until the cord just began to slip over the nylon canopy fabric wrapped around the pulley. This was repeated three or four times. Twists given to the shaft were for the purpose of attempting to overcome the creep properties of the parachute materials. In addition, the forces registered on the Brown recorder at the moment of slippage of the nylon cloth were used to determine the static frictional force and coefficient of static friction.

The motor was started and run at the desired speed for one and one-half minutes. If fusion did not occur within this period of time, the motor and chart were stopped, and an additional weight suspended from the free end of the line. The motor was started again and the test run for another one and one-half minutes. If fusion occurred within this period of time, the slack tension, T_1, present is considered to be the maximum slack tension, or the fusion load, F. L. for the lubricant. If fusion did not occur within this period of time, the slack tension was increased until fusion finally occurred. The fusion load for a lubricated cord and scoured cloth is assumed to be a measure of the ability of a lubricant to prevent fusion, i.e., the higher the fusion load associated with a lubricant the better it is as a parachute lubricating agent.

APPENDIX C

MATERIALS USED

The materials used on all tests were as follows: Scoured nylon parachute cord, Specification MIL-C-5040, Type III, natural; and scoured nylon parachute cloth, Specification MIL-C-7020, Type I, (1.1 ounces per square yard, ripstop, natural).

The cord and cloth were always scoured in order to remove any foreign materials which might introduce an error in the study of lubricants.

The per cent extractables before and after scouring for nylon suspension line and nylon canopy material were determined by U. S. P. ether in soxhlet extractors, for a minimum of twenty cycles. The per cent extractables for nylon suspension line were found to be more than 1.01% before scouring and less than 0.06% after scouring. The per cent extractables for the nylon canopy material were found to be more than 0.075% before scouring and less than 0.002% after scouring. The per cent extractables, however, of the lines used for evaluating n-dodecyl alcohol, and 1-octadecanol, were found to be 0.50% before scouring and 0.30% after scouring. This slight decrease in per cent extractables was caused by the oxalic acid present in one of the wash baths when these lines were scoured. As nylon has an affinity for oxalic acid, a small amount of the acid was retained after washing by the nylon. The amount of oxalic acid present was probably too small to introduce any variations, or errors in the results, since the amount of lubricant applied on the line for testing was high enough to coat the entire surface of the line.

Chemically pure high molecular weight fatty acids, alcohols, and esters were used. Their purity was checked by the melting or boiling point method. No significant differences were found in the values as compared to values given in the literature. A few commercial samples of lubricants were also tested. No attempt was made to purify these materials.

APPENDIX D

APPLICATION OF LUBRICANTS

Essentially, the method, apparatus (Figure 2), and parachute materials used in this study of testing and of applying lubricants are the same as previously presented (WADC TR 54-323, Part 1). However, some modifications were necessary and are discussed in the following sections.

The shroudline was lubricated with a 10 ± 1% pickup and, as before, run against scoured ripstop cloth. (See Appendix E for a table of a summary of treatments.) This was done because the application of the correct amount of lubricant to the line is simpler and more accurate than application to the parachute cloth. Also, as heavy amounts of lubricant will be needed to prevent line burns the presence of these large amounts on line will cause less difficulty than if the lubricant were applied to the cloth. Our method of applying lubricant to line may be considered to be a more practical procedure.

Each test consisted of a set of five samples; a number often used in the rapid testing of textile materials.

An apparatus was constructed to obtain uniform samples. A schematic diagram of the apparatus used for applying a lubricant on the line is shown in Figure 4. It consisted of a perforated stainless steel plate placed three-quarters of an inch from the bottom of an 800 ml beaker, forming a false bottom. A stainless steel tube was fixed at the center of the false bottom and the false bottom divided into five equal parts by perforated plates. These plates have the tube as a common center. The whole device was placed in an 800 ml beaker. Through the center of the stainless steel tube, a shaft of an air stirrer was passed with the propeller rotating between the false bottom and the bottom of the beaker.

Samples of parachute cord seventy inches in length were conditioned for at least twenty-four hours and weighed. A 500 ml solution of predetermined strength to give a 10 ± 1% pickup of lubricant on the line was prepared and poured into the beaker containing the stainless steel separator. The air stirrer was started and each of the samples placed in the compartmented beaker. At the end of ten minutes the stirrer was stopped and the samples were removed from the solution without squeezing. The samples were suspended from the hooks of a bar, allowed to dry for twenty-four hours under atmospheric conditons, and after drying were conditioned for another twenty-four hours. At the end of this time, the samples were weighed.

The increase in weight of the line after it was dipped in the solution of a lubricant divided by the original weight of the line and multiplied by 100, constitutes the per cent pickup (%P) of the line.

The relatively high percentage pickup used in our program should eliminate, or minimize, any small variations in experimental results because of minor differences in the per cent pickup between lubricated lines.

APPLICATION OF LUBRICANTS

All the fatty alcohols, fatty acids, and fatty esters were applied to the line from a 15% solution in ethanol, with the exception of the stearic acid, n-dodecyl alcohol, and 1-octadecanol, which were applied from a 10% solution in ethanol. **Cationic Compound A** , Arquad 2HT, and Polyethylene Glycol 400 (Mono) Laurate were applied from a 10%, 15%, 15% and 10% emulsion in water respectively. In addition, to observe any possible effect of solvent upon the frictional force and fusion load, a second application of the **Cationic Compound A** , Arquad 2C, Arquad 2HT, and Polyethylene Glycol 400 (Mono) Laurate was made from solutions of 9% in acetone, 13% in acetone, 15% in acetone, and 10% in alcohol respectively.

APPENDIX E

SUMMARY OF THE TREATMENT OF SHROUDLINE

Lubricant	Source	Applied From	Physical Characteristics of Treated Line
n- Caprylic acid C. P.	Eastman Organic Chemicals	15% solution in ethanol	Oily
n-Capric acid C. P.	Matheson Coleman & Bell Co.	15% solution in ethanol	Oily
Lauric acid C. P.	Eastman Organic Chemicals	15% solution in ethanol	Lubricant flakes off, stiff
Myristic acid C. P.	Eastman Organic Chemicals	15% solution in ethanol	Lubricant flakes off, stiff
Stearic acid C. P.	Eastman Organic Chemicals	10% solution in ethanol	Lubricant flakes off, stiff
n-Dodecyl alcohol C. P.	Eastman Organic Chemicals	10% solution in ethanol	Oily
Myristyl alcohol C. P.	Eastman Organic Chemicals	15% solution in ethanol	Slightly oily
1-Octadecanol C. P.	Eastman Organic Chemicals	10% solution in ethanol	Lubricant flakes off, stiff
Ethyl Laurate C. P.	Matheson Coleman & Bell Co.	15% solution in ethanol	Slightly oily
Ethyl Myristate C. P.	Matheson Coleman & Bell Co.	15% solution in ethanol	Slightly oily

APPENDIX E continued

SUMMARY OF THE TREATMENT OF SHROUDLINE

Lubricant	Source	Applied From	Physical Characteristics of Treated Line
Ethyl Stearate C. P.	Matheson Coleman & Bell Co.	15% solution in ethanol	Slightly oily
Cationic Compound A (cationic)		10% emulsion in water	Sticky, stiff
Cationic Compound A (cationic)		9% solution in acetone	Sticky, stiff
Arquad 2C (anionic)	Armour Chemical Division	15% emulsion in water	Slightly sticky and oily
Arquad 2C (anionic)	Armour Chemical Division	13% solution in acetone	Slightly sticky and oily
Arquad 2HT (anionic)	Armour Chemical Division	15% emulsion in water	Sticky and slightly oily
Arquad 2HT (anionic)	Armour Chemical Division	15% solution in acetone	Sticky and slightly oily
Polyethylene Glycol 400 (Mono) Laurate	Glyco Products Co.	10% emulsion in water	Slippery
Polyethylene Glycol 400 (Mono) Laurate	Glyco Products Co.	10% emulsion in ethanol	Slippery

APPENDIX F

EXPLANATION OF SYMBOLS USED IN THE TABLES AND FIGURES

<u>Symbols Used</u>

RH	Relative Humidity (%)
T_1	Slack Tension (gm)
T_2	Tight or Taut Tension (gm)
μ	Coefficient of Friction
μ_k	Coefficient of Kinetic (or Sliding) Friction
μ_s	Coefficient of Static Friction
θ	Angle of Contact or Wrap (^{o})
^oF	Degrees Fahrenheit
v	Velocity (ft/sec)
F_k or F_S	Kinetic or Static Frictional Force, i.e., Slack Tension Subtracted from Tight Tension (gm)
T	Temperature
%P	Per Cent Pickup
FL	Fusion Load (gm), (Slack Tension at which Fusion Occurs, Based on Five Tests)

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1. Bowden, F. P., and Tabor, D., The Friction and Lubrication of Solids, p 195, Oxford Clarendon Press, New York (1950).

2. Ibid, p 189.

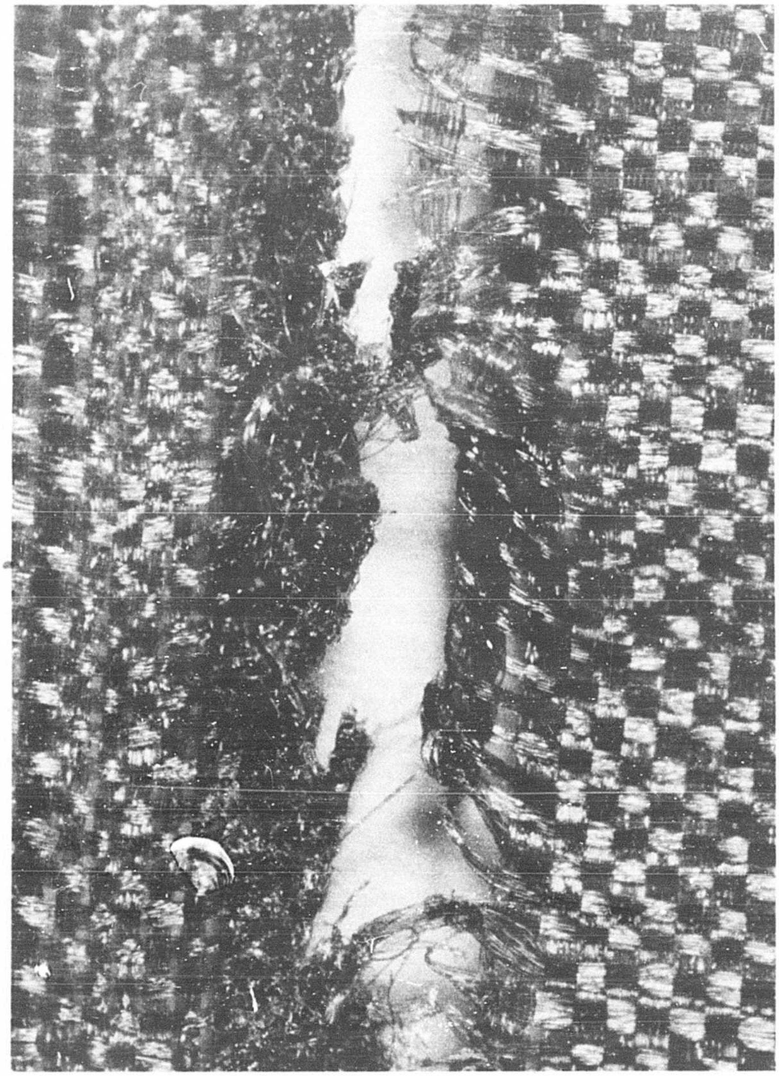


FIGURE 1

A TYPICAL PARACHUTE LINE BURN

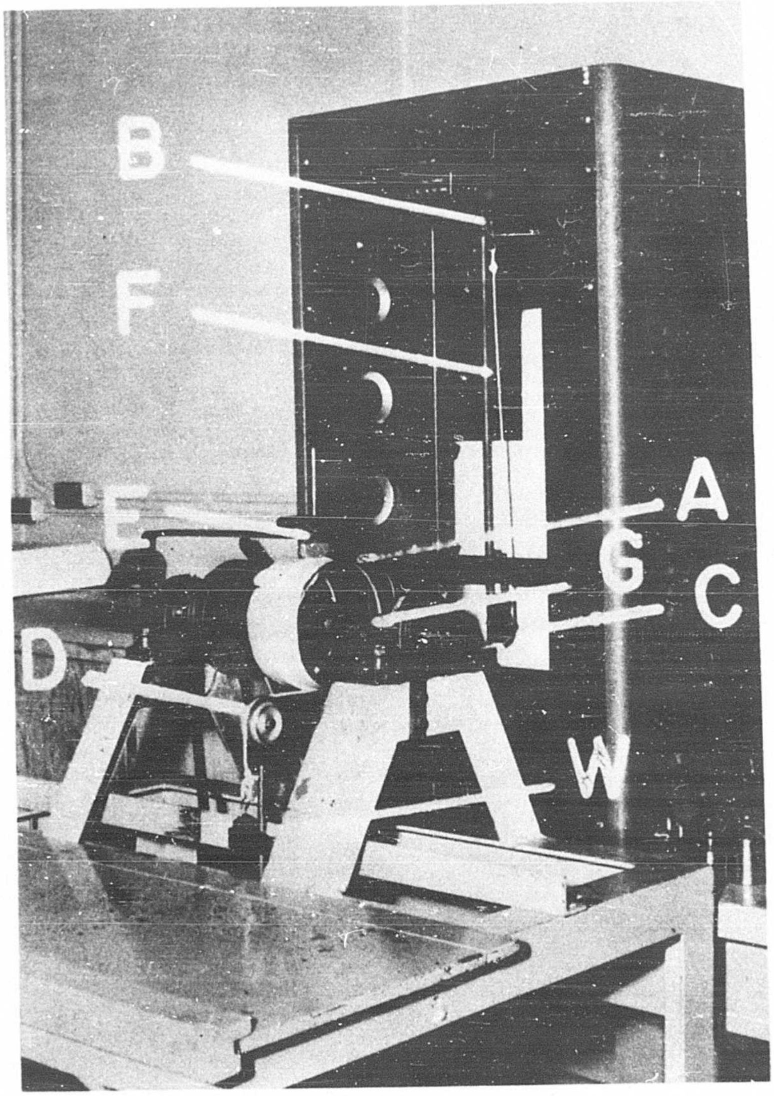


FIGURE 2

HIGH SPEED FRICTION APPARATUS

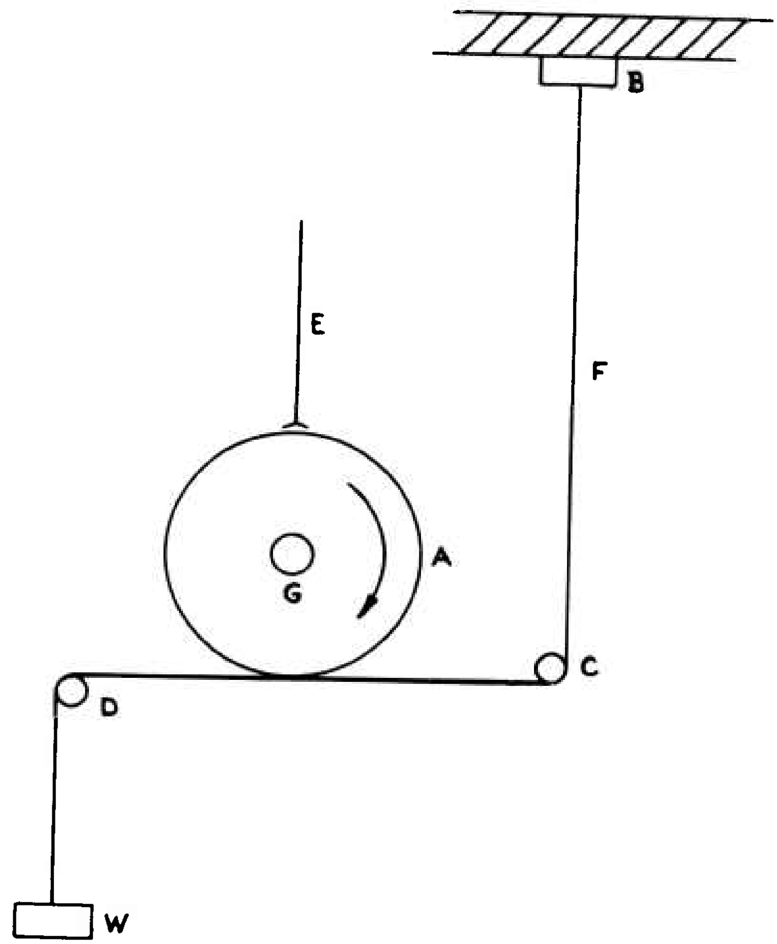


FIGURE 3. DIAGRAM OF HIGH SPEED FRICTION APPARATUS.

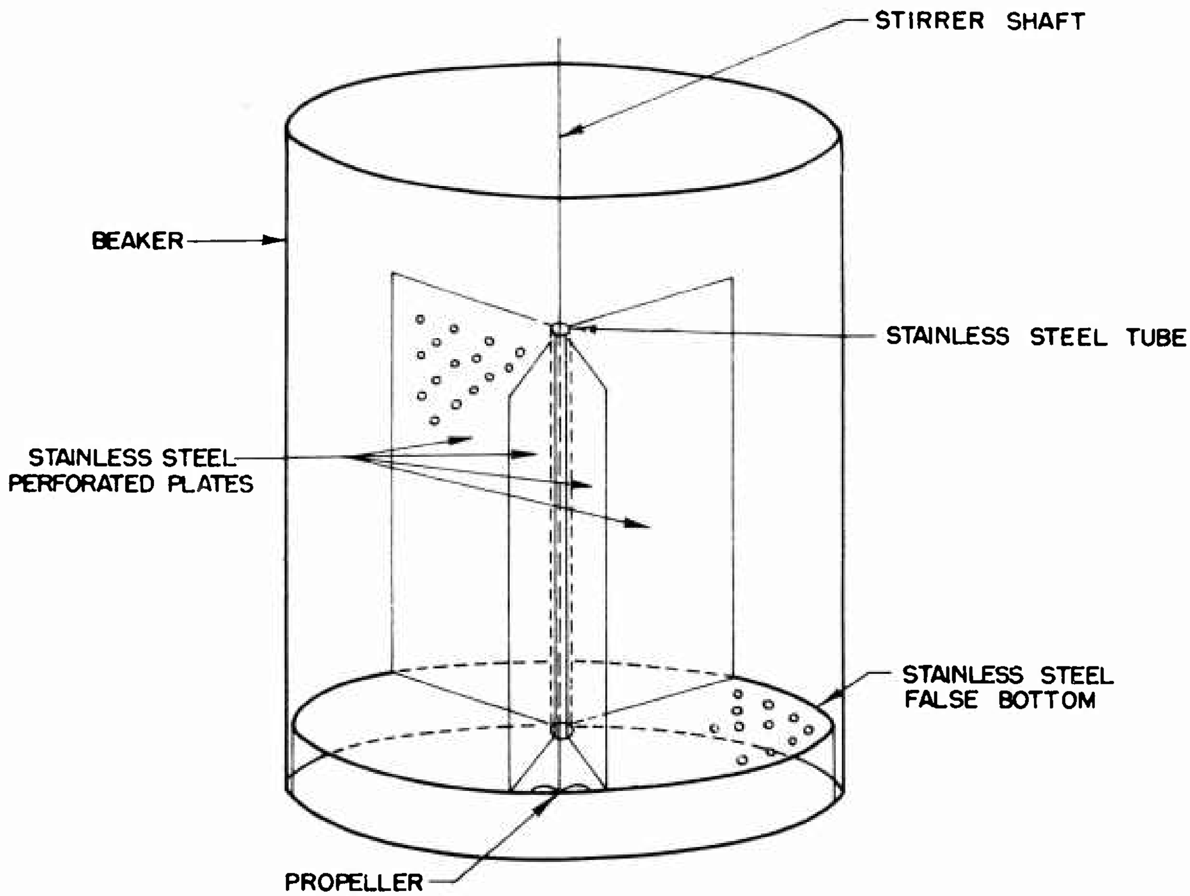
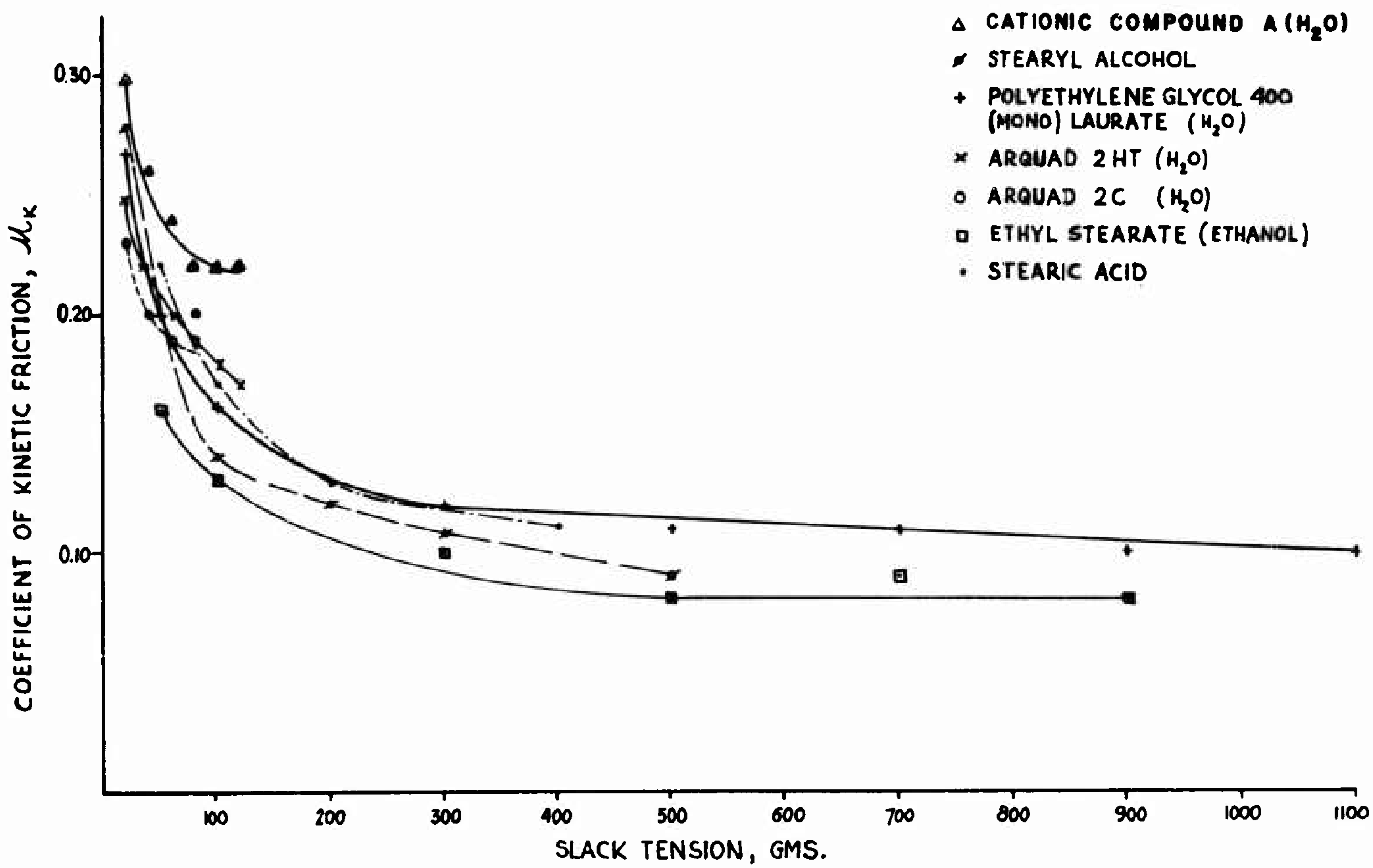
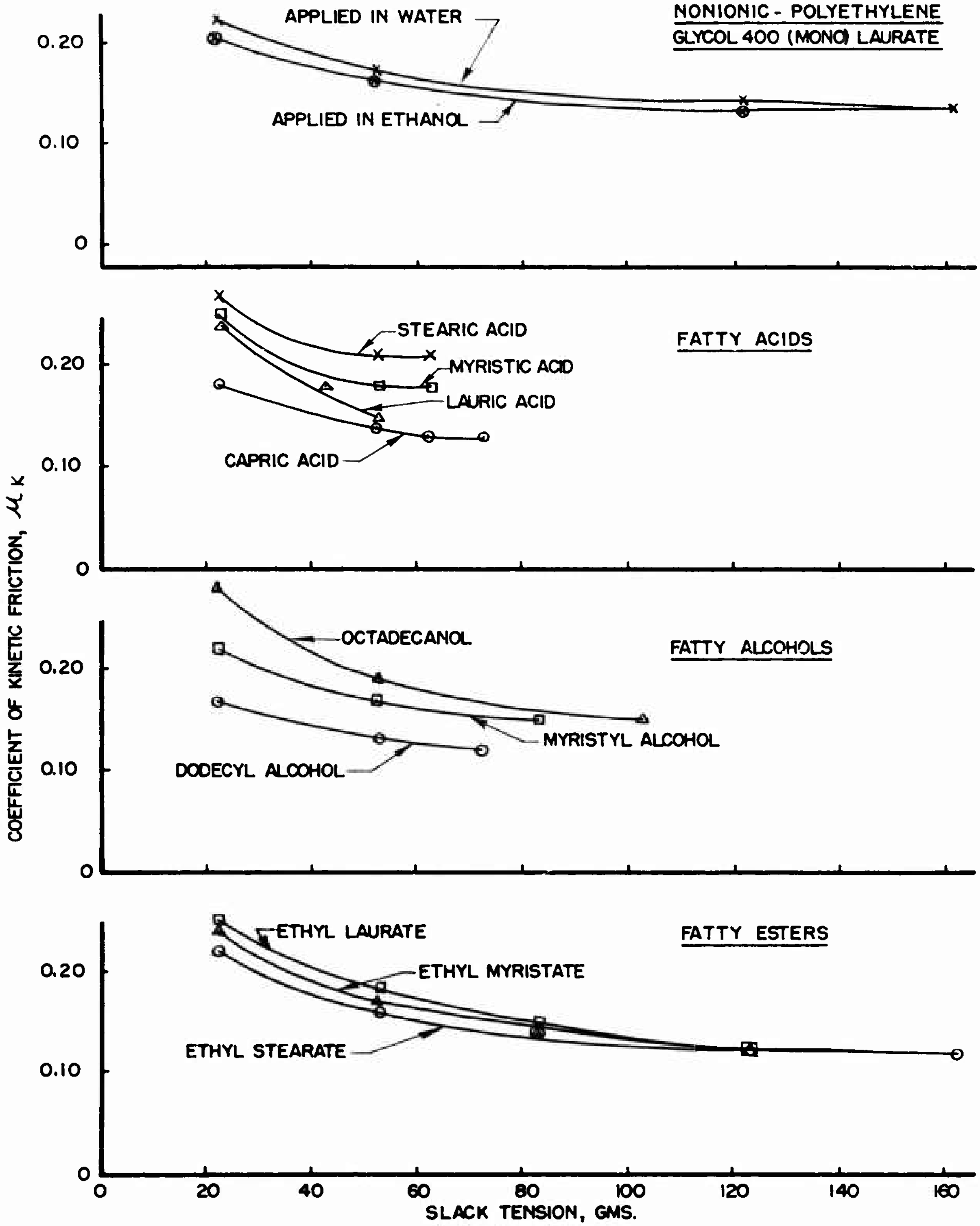


FIGURE 4. APPARATUS FOR APPLYING LUBRICANT TO SHROUD LINE



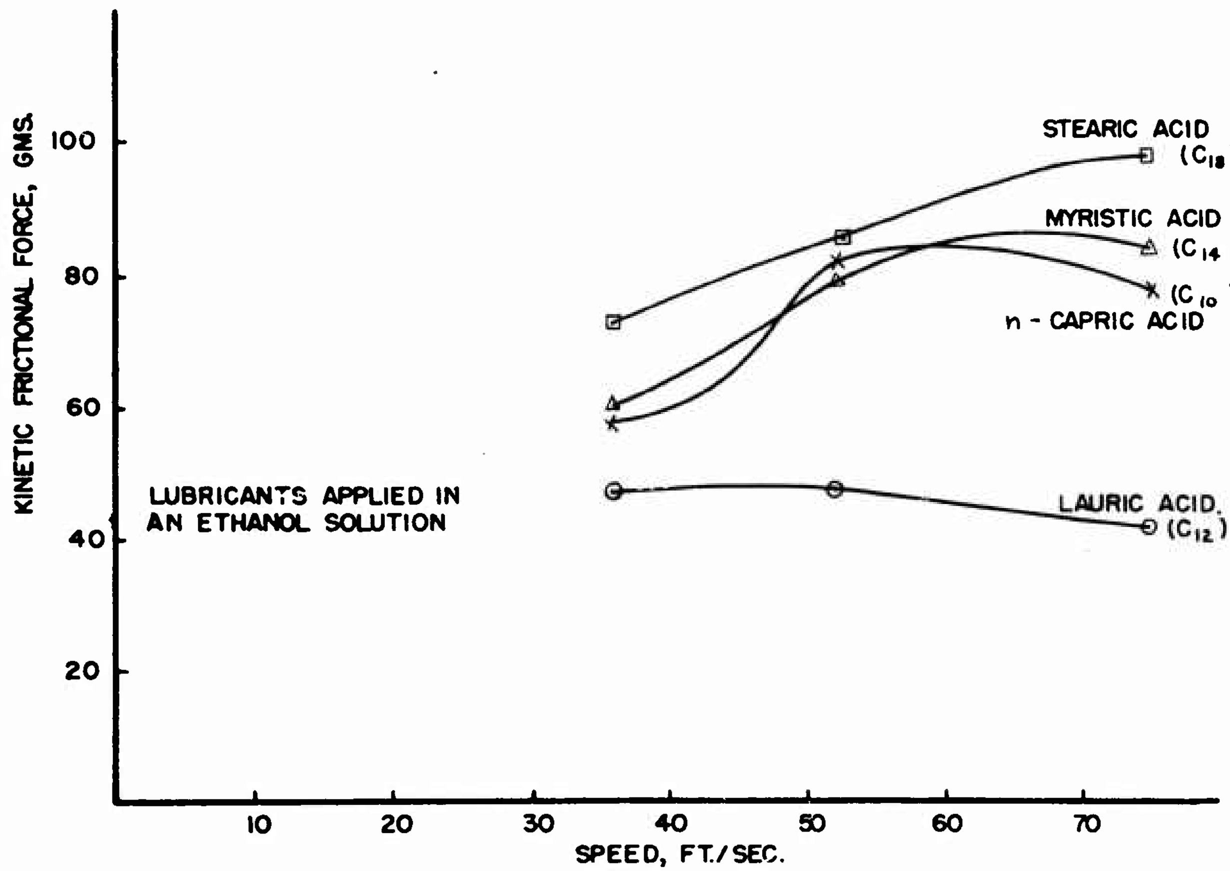
A. SPEED = 25 FT./SEC.

FIGURE 5. THE EFFECT OF SLACK TENSION ON THE COEFFICIENT OF KINETIC FRICTION



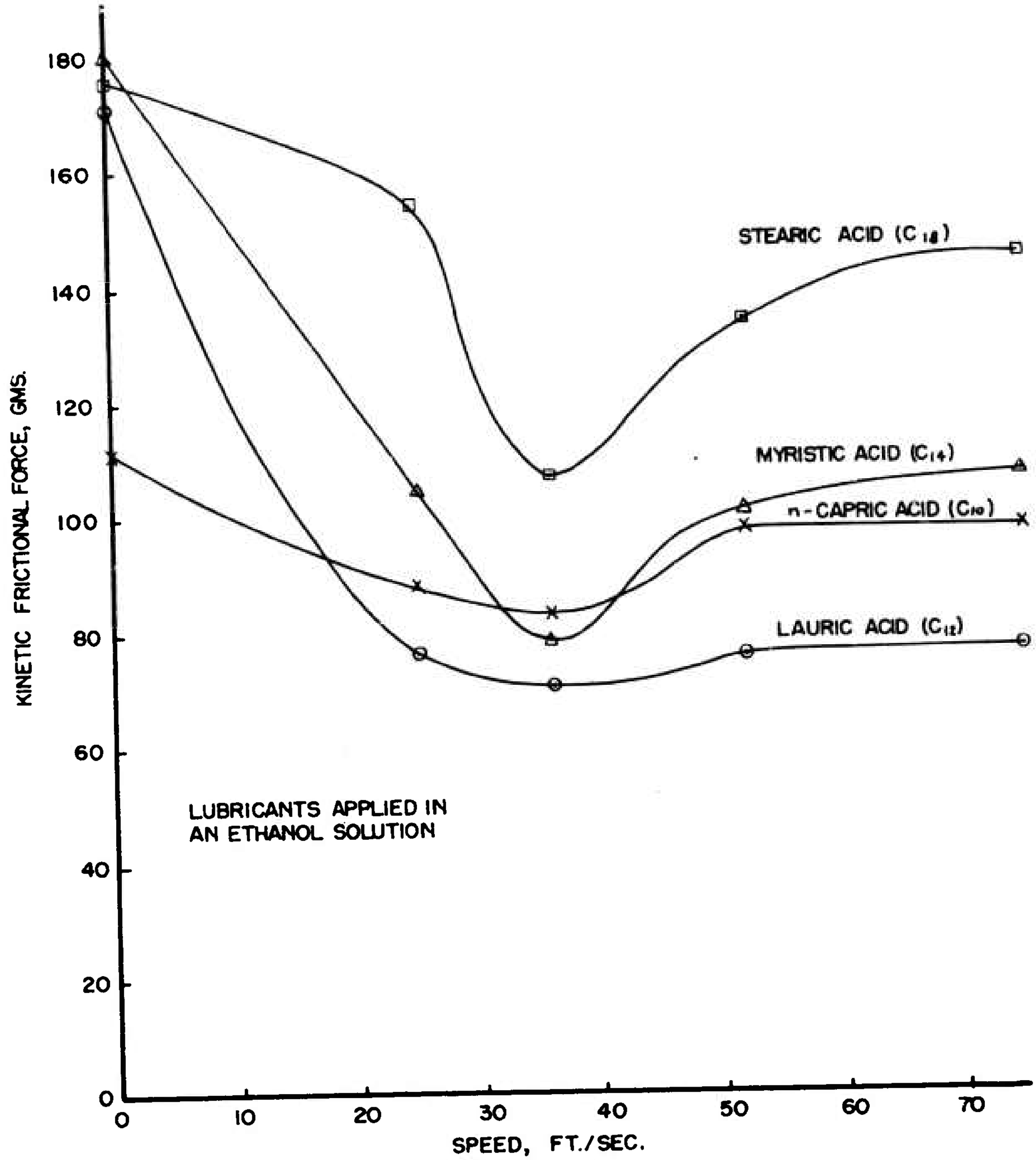
B. SPEED=75 FT./SEC.

FIGURE 5. (CONTINUED) THE EFFECT OF SLACK TENSION ON THE COEFFICIENT OF KINETIC FRICTION



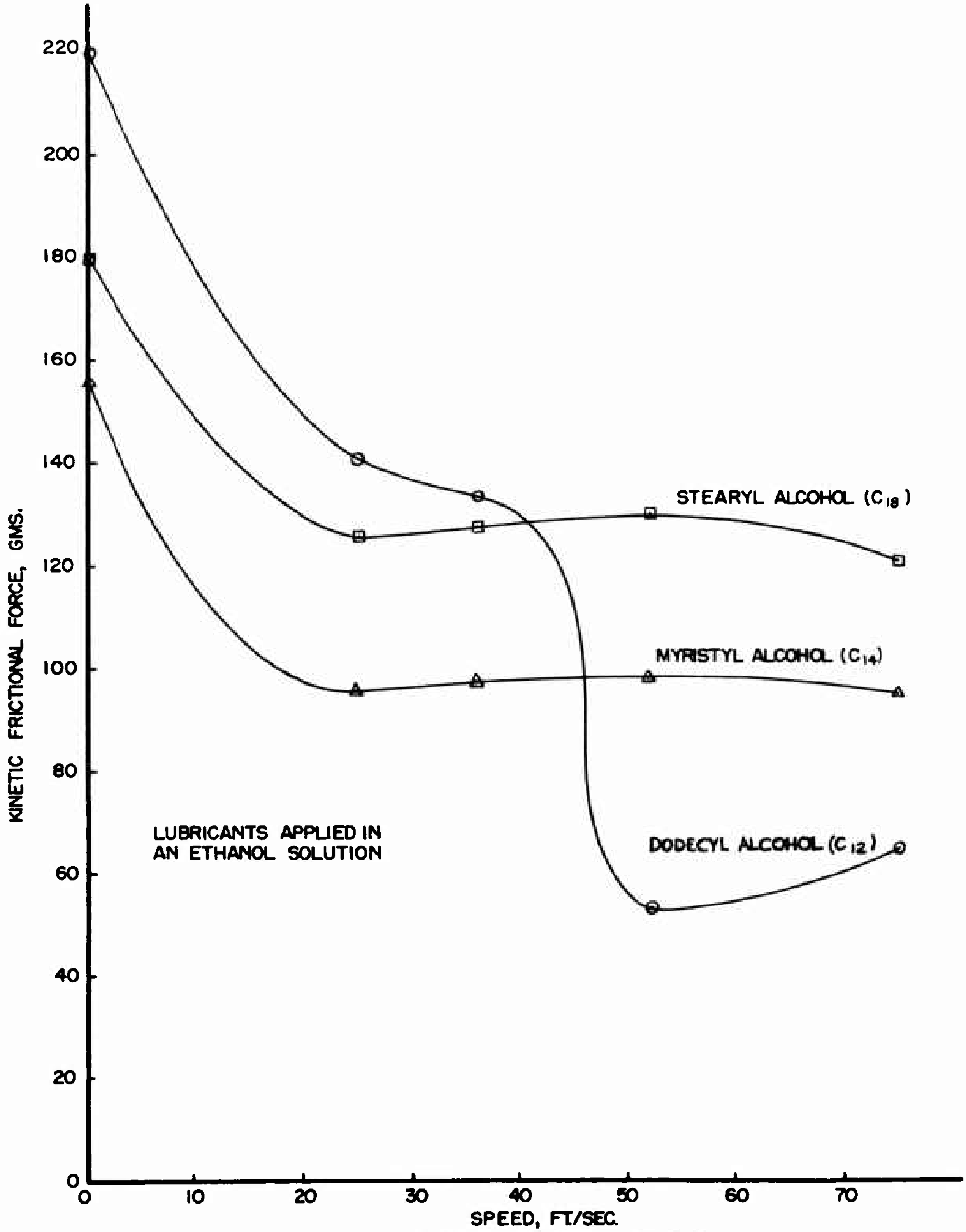
A SLACK TENSION = 22 GMS.

FIGURE 6. THE EFFECT OF SPEED ON KINETIC FRICTIONAL FORCE FOR SURFACES LUBRICATED WITH FATTY ACIDS



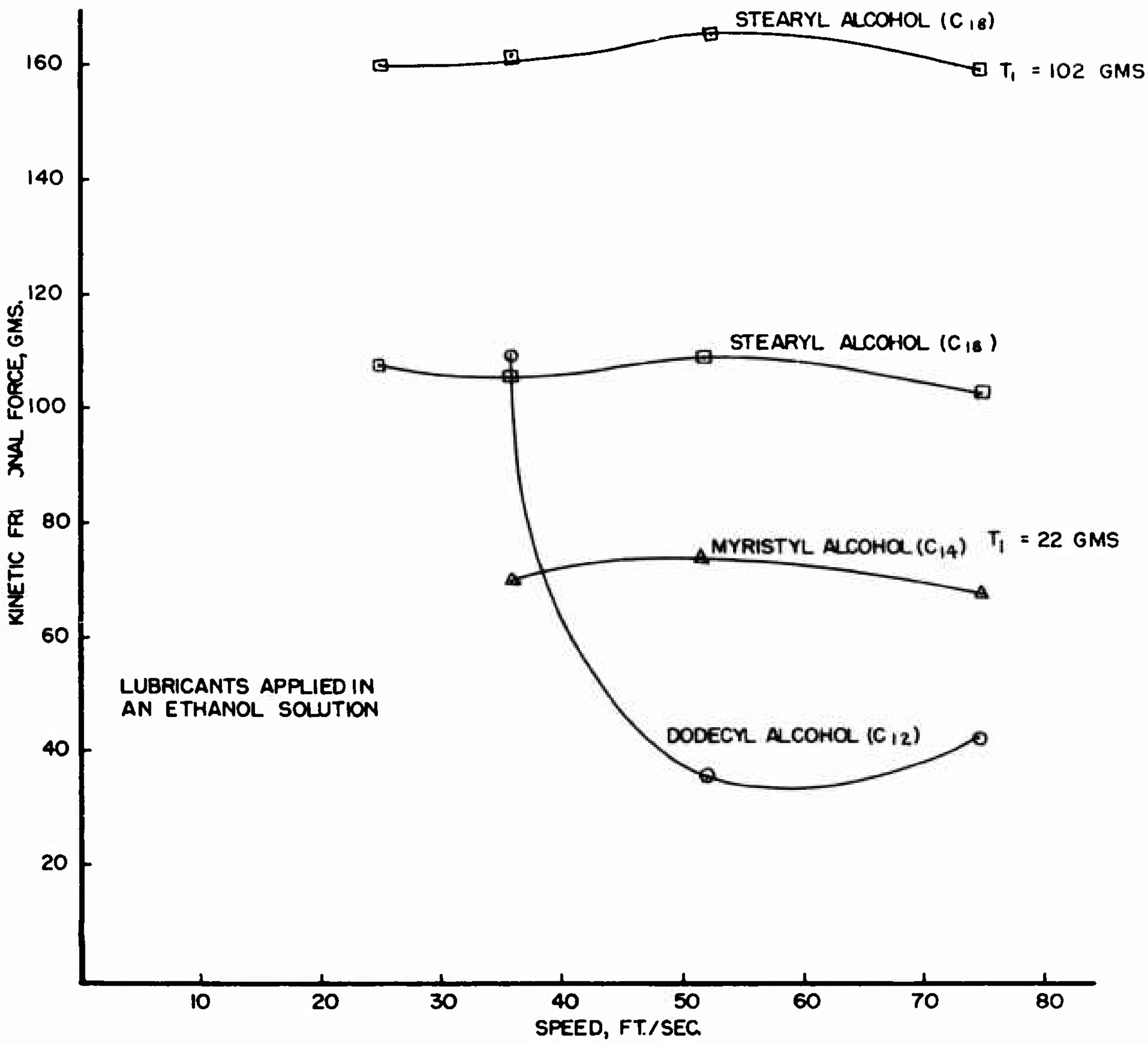
B. SLACK TENSION = 52 GMS.

FIGURE 6. THE EFFECT OF SPEED ON KINETIC FRICTIONAL FORCE
(CONTINUED) FOR SURFACES LUBRICATED WITH FATTY ACIDS



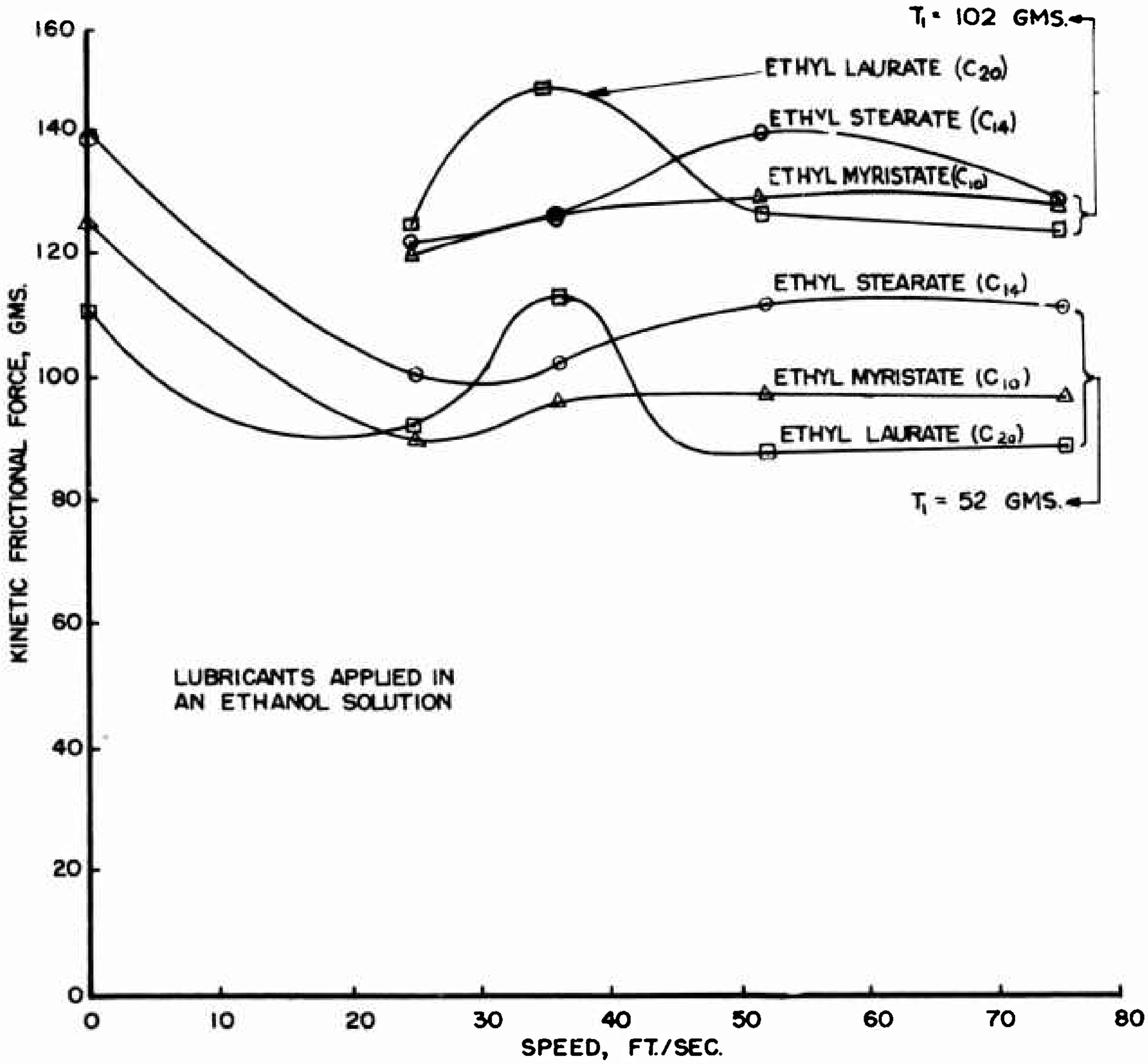
A. SLACK TENSION = 52 GMS.

FIGURE 7. THE EFFECT OF SPEED ON KINETIC FRICTIONAL FORCE FOR SURFACES LUBRICATED WITH FATTY ALCOHOLS



B. SLACK TENSION = 22 AND 102 GMS.

FIGURE 7. (CONTINUED) THE EFFECT OF SPEED ON KINETIC FRICTIONAL FORCE FOR SURFACES LUBRICATED WITH FATTY ALCOHOLS



SLACK TENSION = 52 AND 102 GMS.

FIGURE 8. THE EFFECT OF SPEED ON KINETIC F CTIONAL FORCE FOR SURFACES LUBRICATED WITH . TY ESTERS

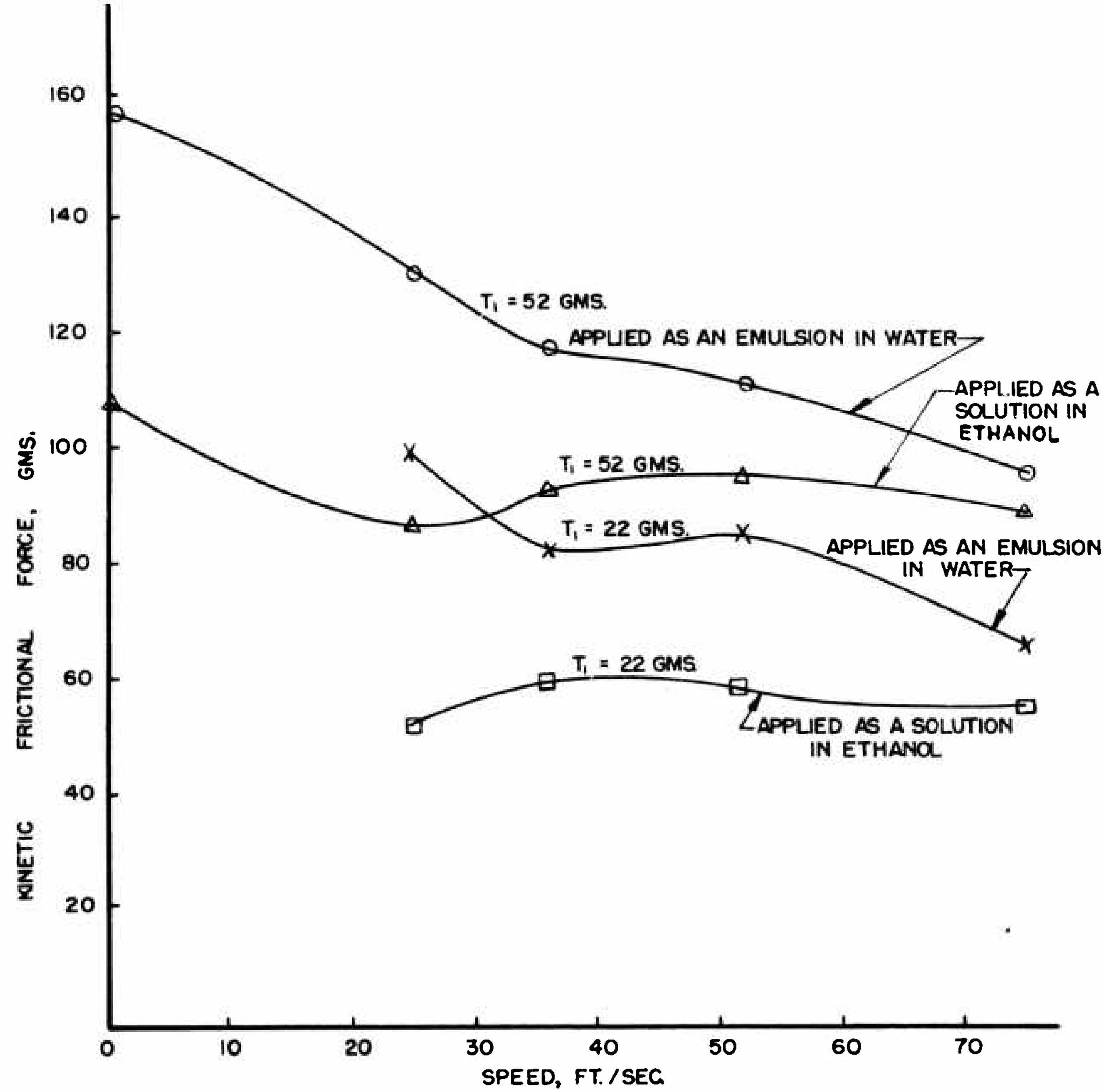


FIGURE 9. THE EFFECT OF SPEED ON KINETIC FRICTIONAL FORCE FOR SURFACES LUBRICATED WITH POLYETHYLENE GLYCOL 400 (MONO) LAURATE

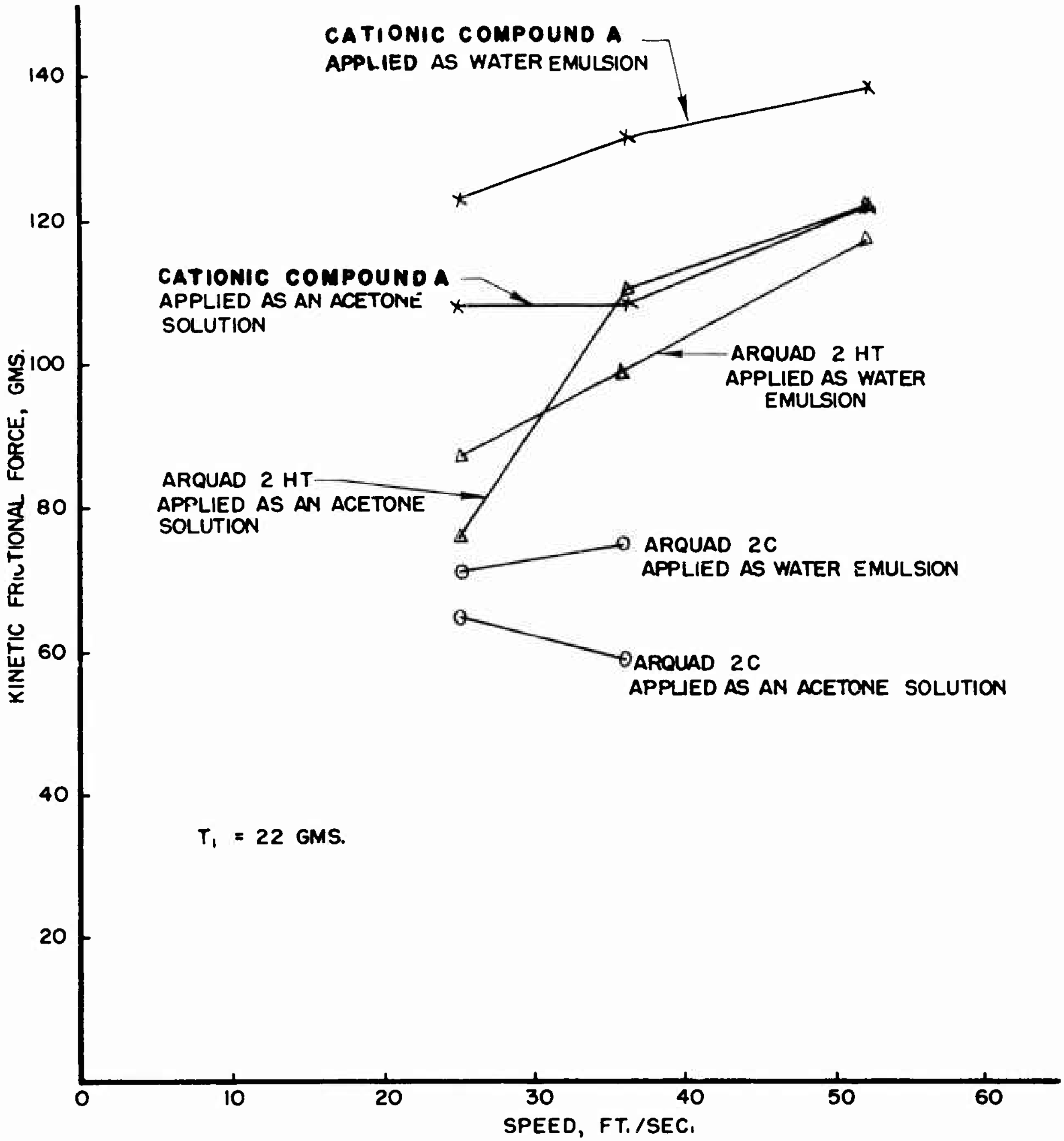


FIGURE 10. THE EFFECT OF SPEED ON KINETIC FRICTIONAL FORCE FOR SURFACES LUBRICATED WITH SURFACE ACTIVE AGENTS

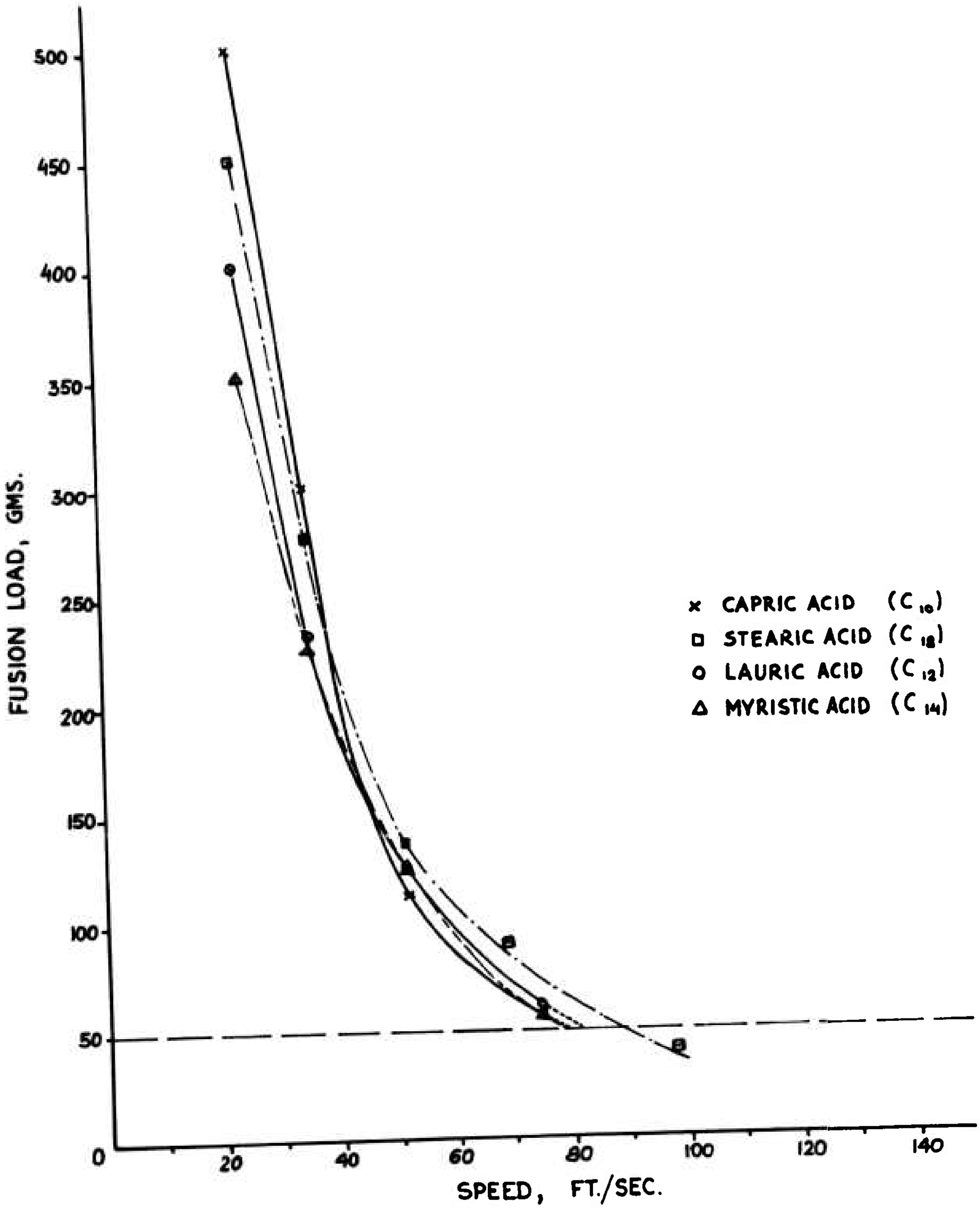


FIGURE 11. THE EFFECT OF SPEED ON THE FUSION LOAD FOR SURFACES LUBRICATED WITH FATTY ACIDS.

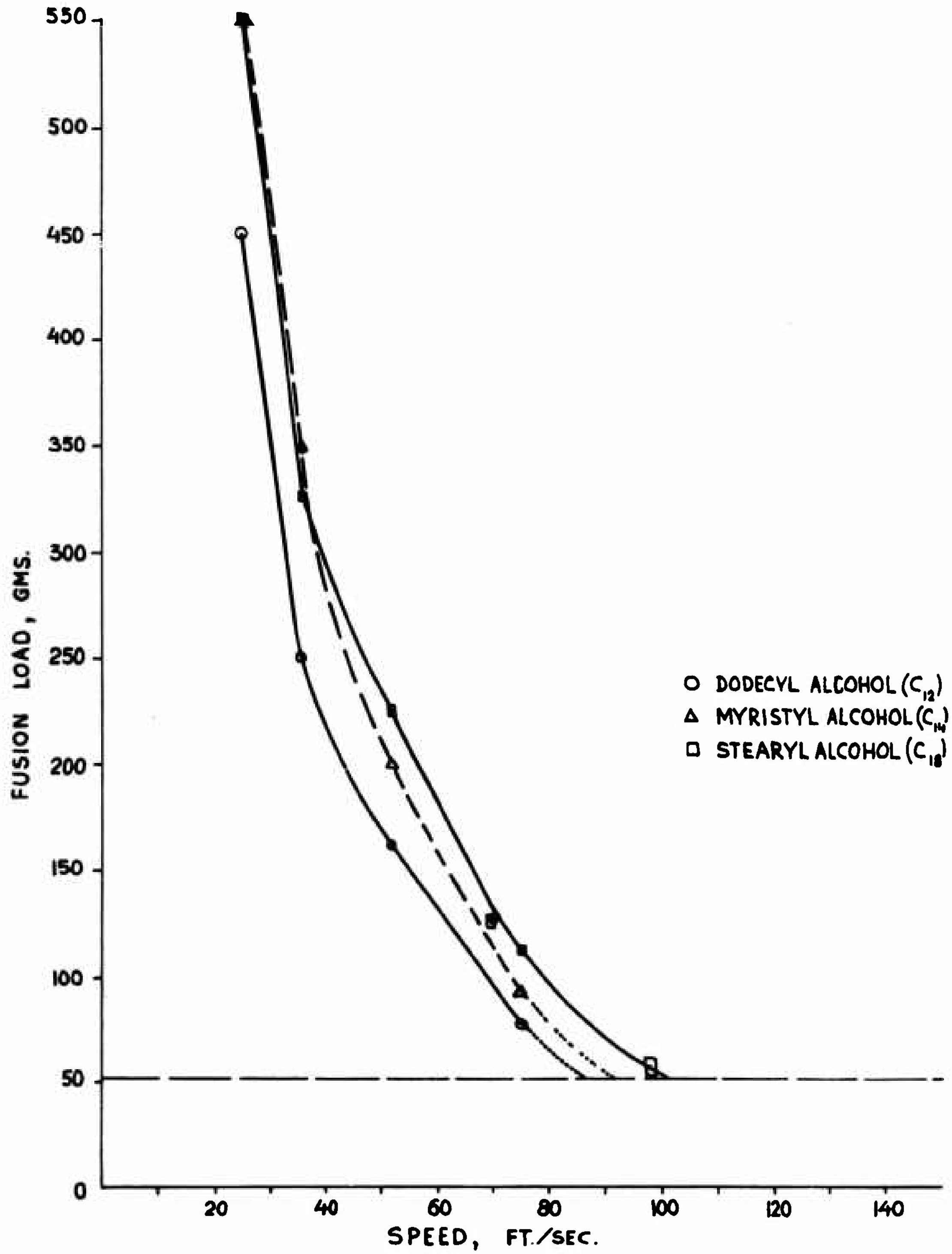


FIGURE 12. THE EFFECT OF SPEED ON THE FUSION LOAD FOR SURFACES LUBRICATED WITH FATTY ALCOHOLS.

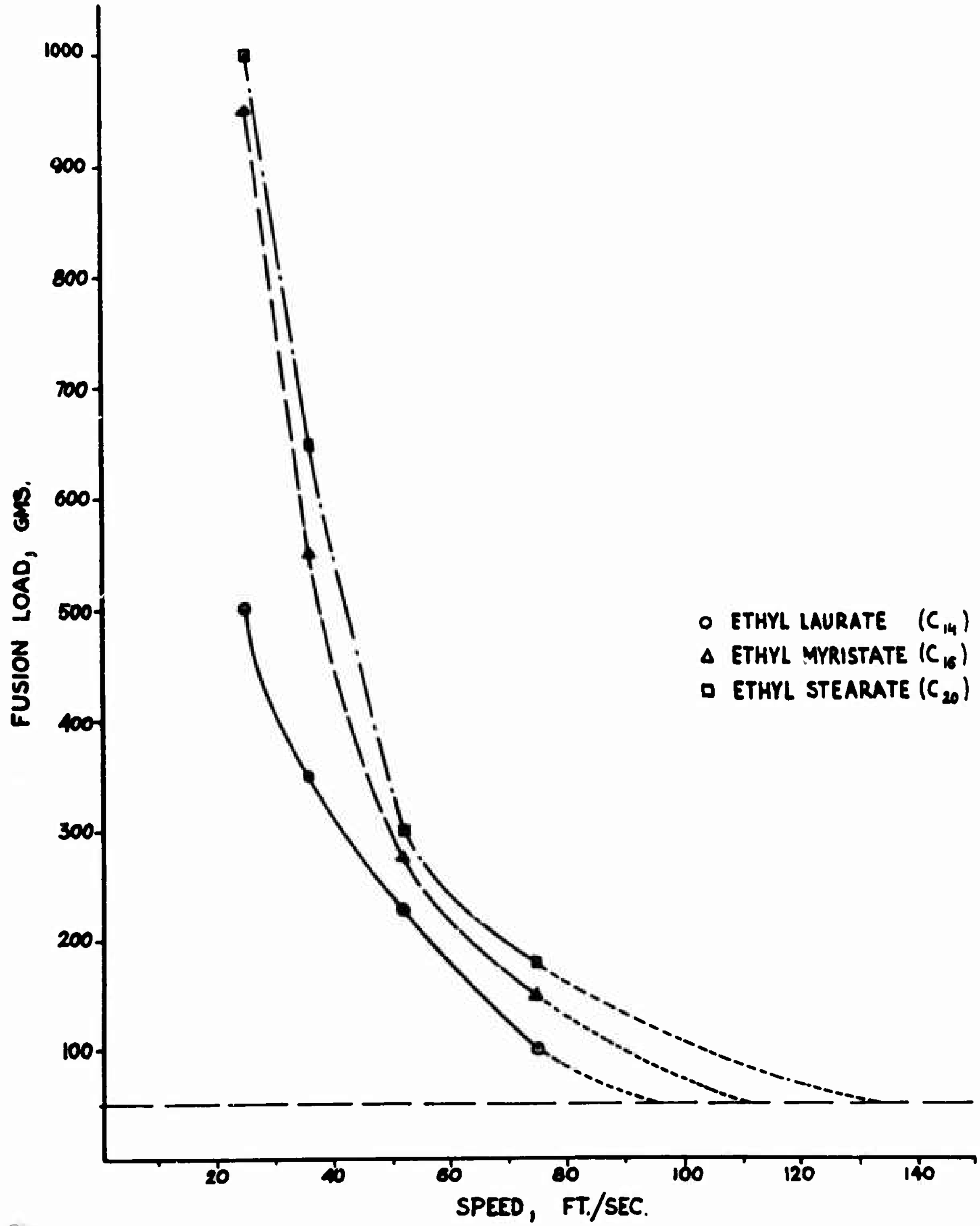


FIGURE 13. THE EFFECT OF SPEED ON THE AVERAGE FUSION LOAD FOR SURFACES LUBRICATED WITH FATTY ESTERS.

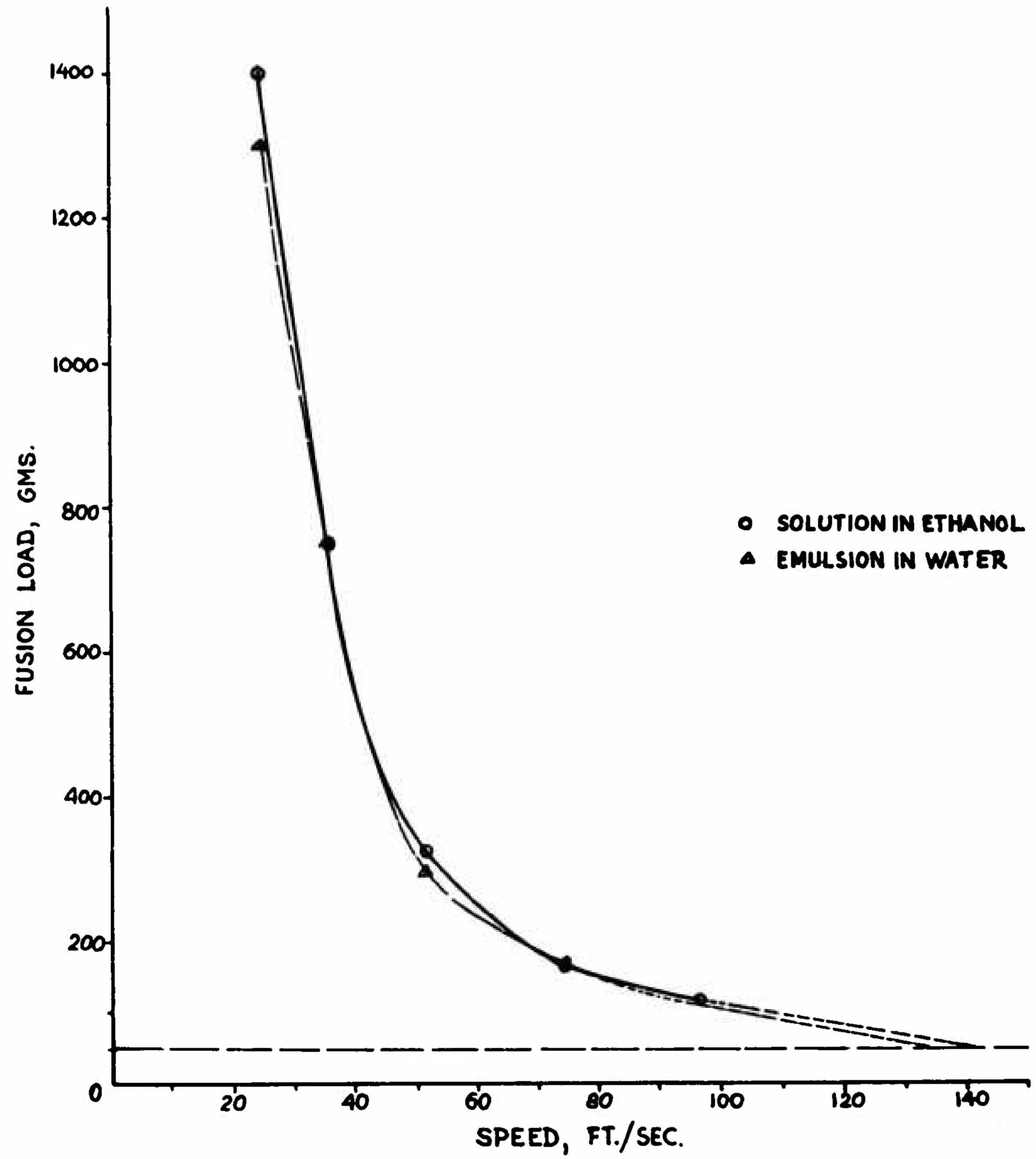


FIGURE 14. THE EFFECT OF SPEED ON THE FUSION LOAD FOR SURFACES LUBRICATED WITH A NONIONIC AGENT, POLYETHYLENE GLYCOL 400 (MONO) LAURATE.

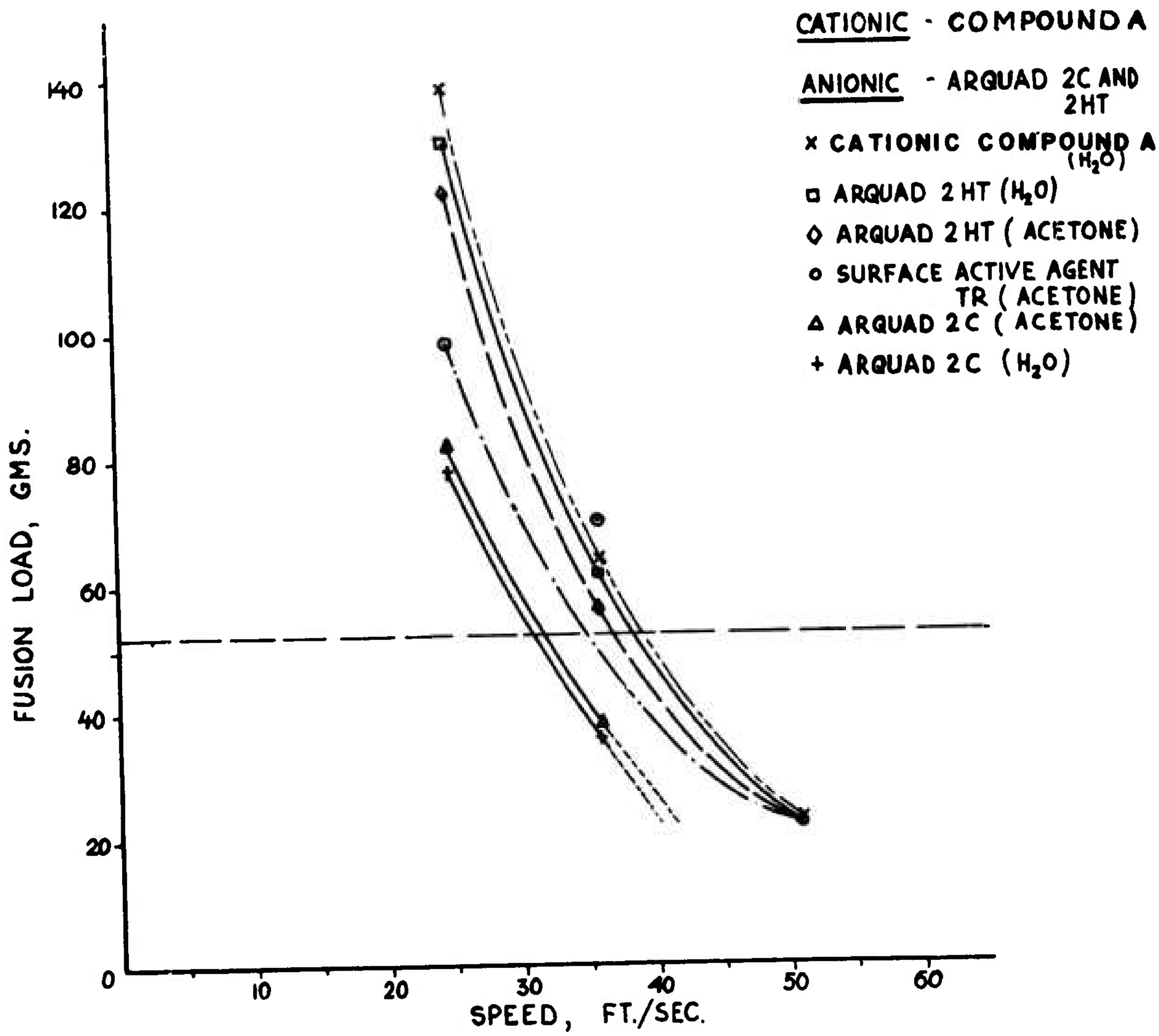


FIGURE 15. THE EFFECT OF SPEED ON THE FUSION LOAD FOR SURFACES LUBRICATED WITH CATIONIC AND ANIONIC AGENTS.

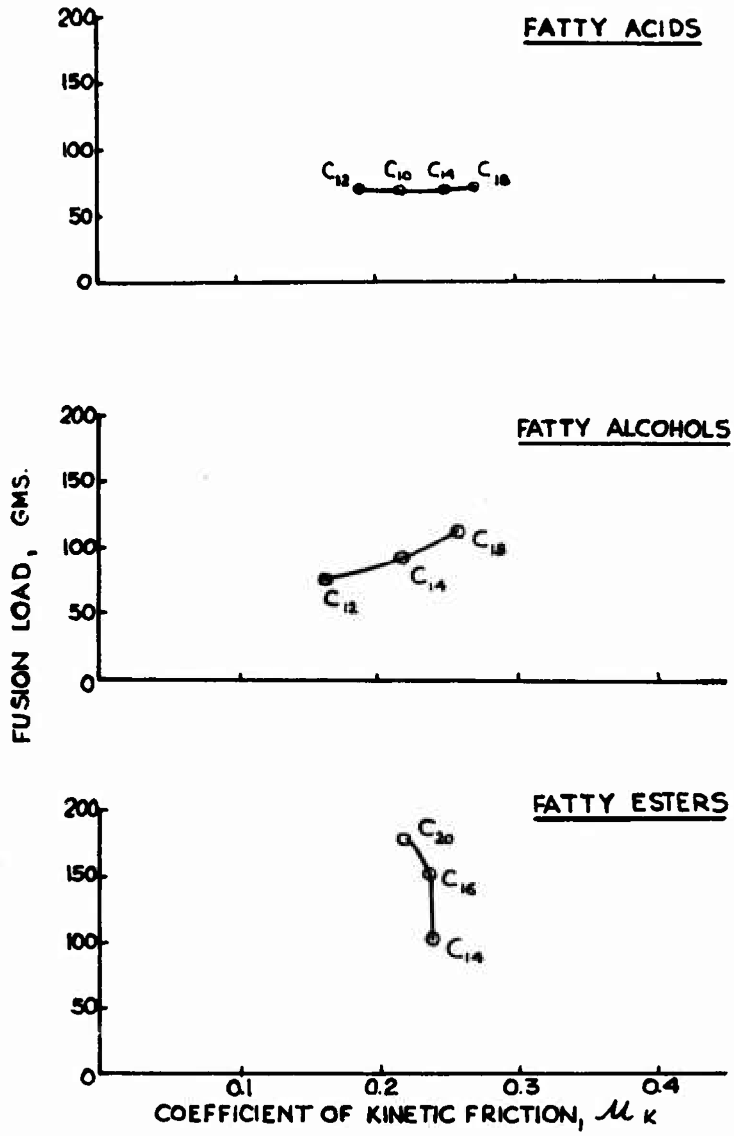


FIGURE 16. THE RELATIONSHIP BETWEEN THE COEFFICIENT OF KINETIC FRICTION AND FUSION LOAD.

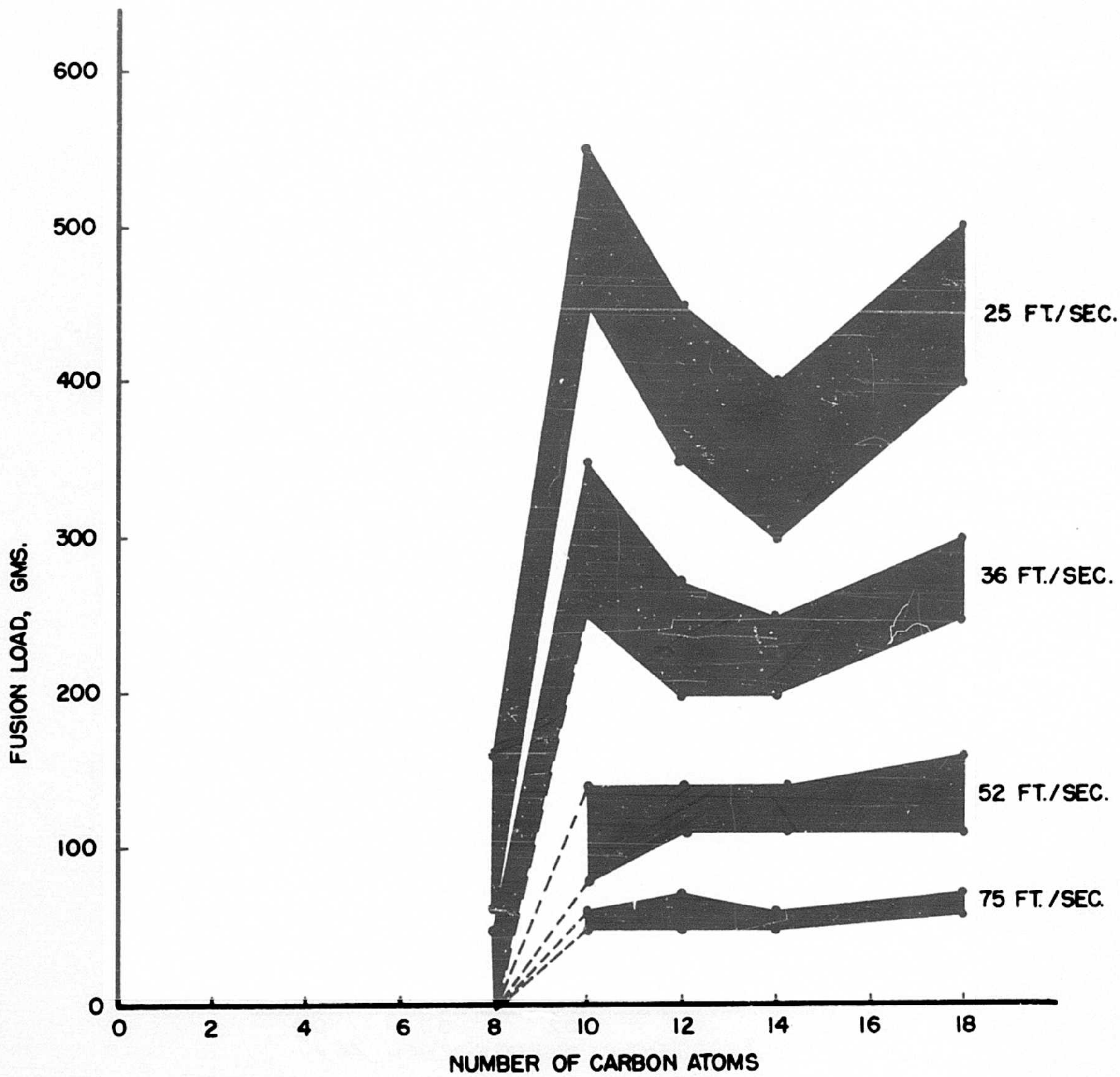


FIGURE 17. THE EFFECT OF MOLECULAR WEIGHT ON THE FUSION LOAD FOR SURFACES LUBRICATED WITH FATTY ACIDS

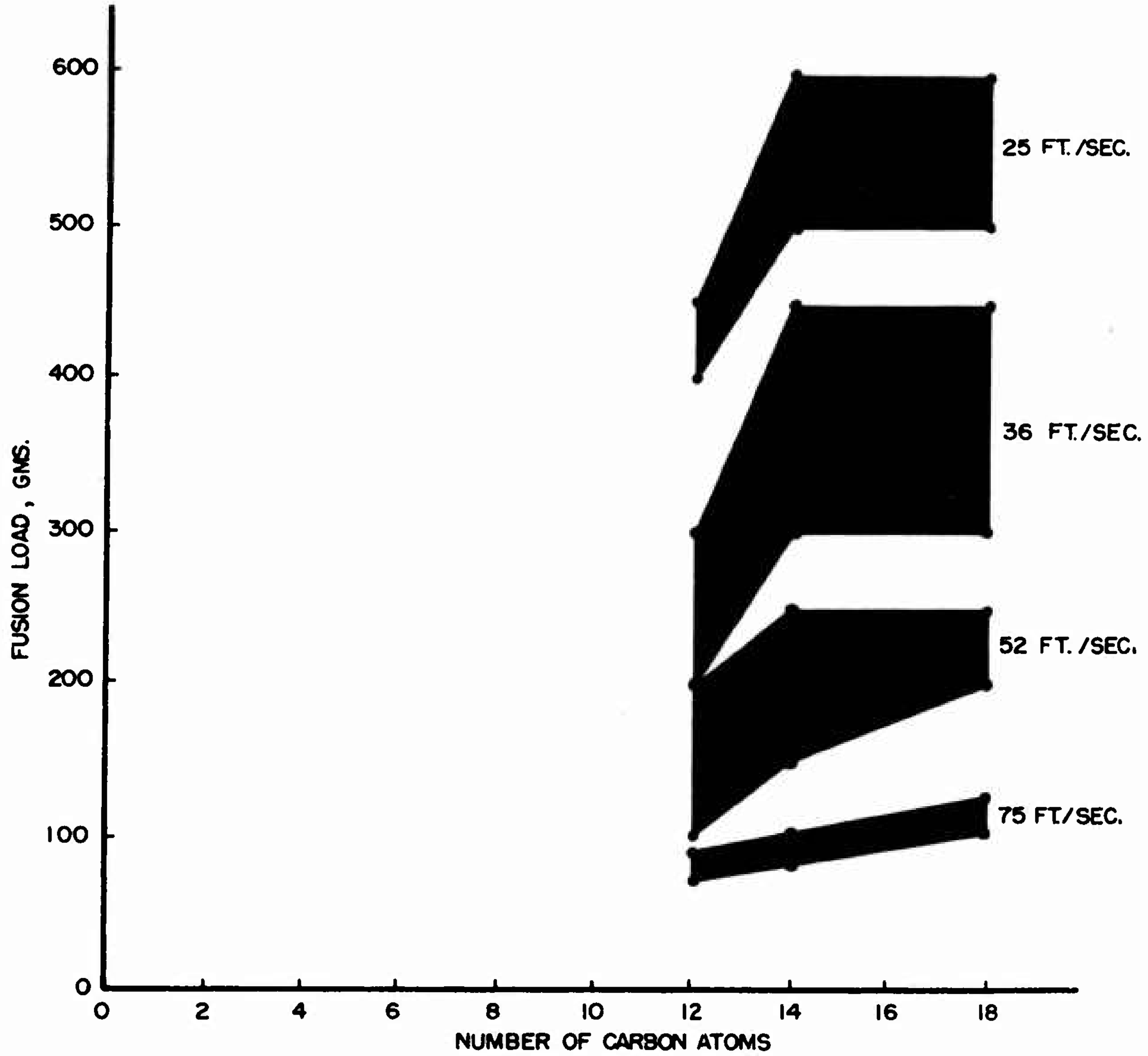


FIGURE 18. THE EFFECT OF MOLECULAR WEIGHT ON THE FUSION LOAD FOR SURFACES LUBRICATED WITH FATTY ALCOHOLS

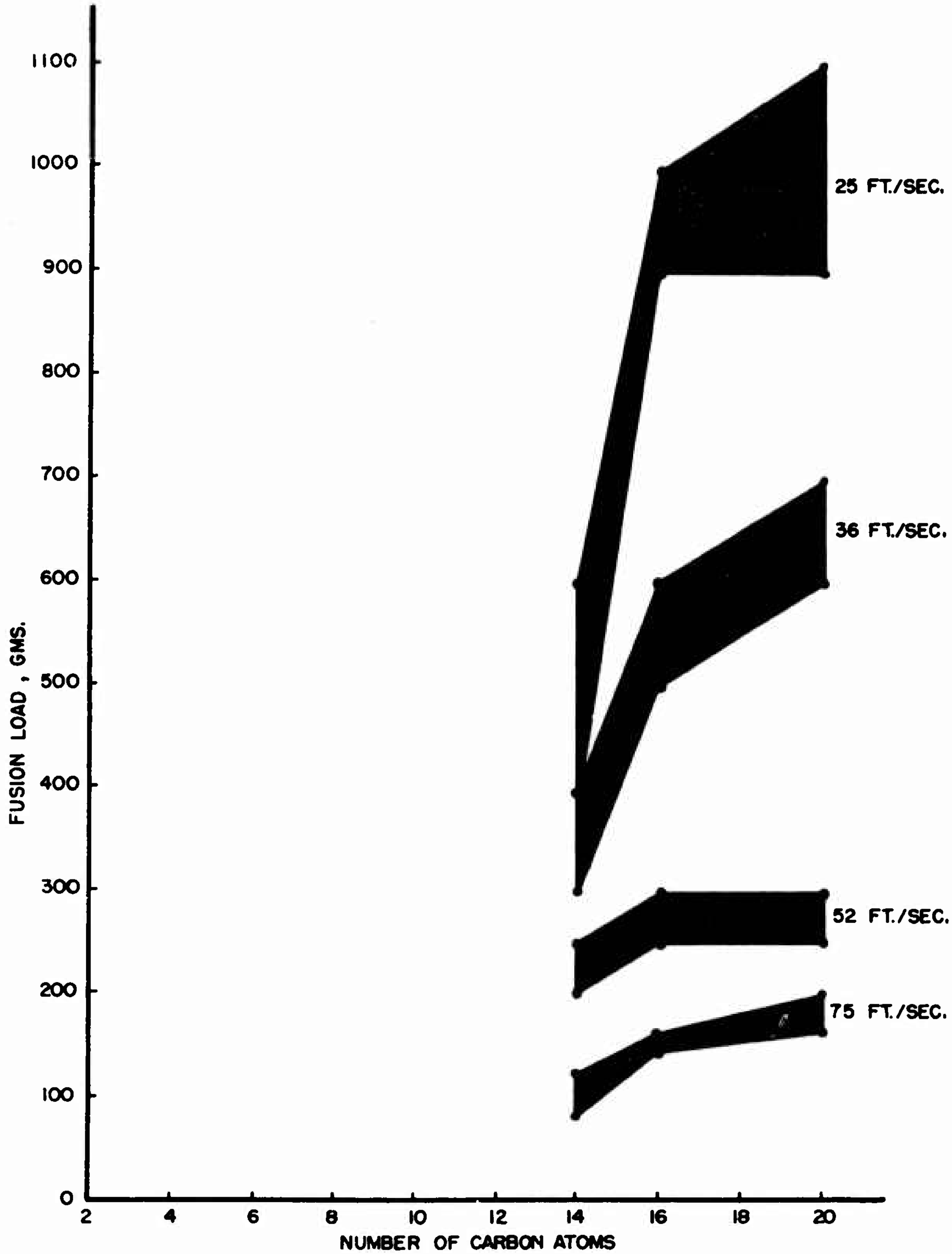


FIGURE 19. THE EFFECT OF MOLECULAR WEIGHT ON THE FUSION LOAD FOR SURFACES LUBRICATED WITH FATTY ESTERS

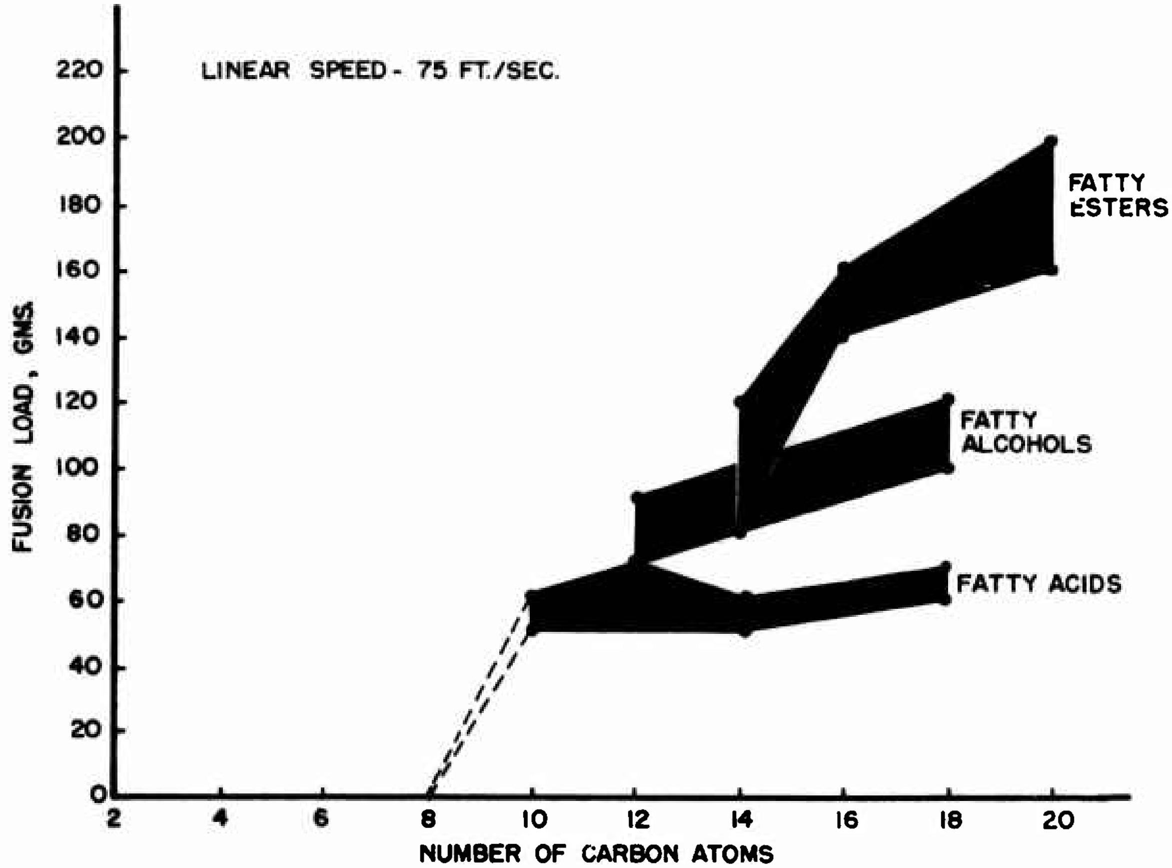


FIGURE 20. THE EFFECT OF MOLECULAR WEIGHT ON THE FUSION LOAD FOR SURFACES LUBRICATED WITH FATTY ACIDS, ALCOHOLS, AND ESTERS

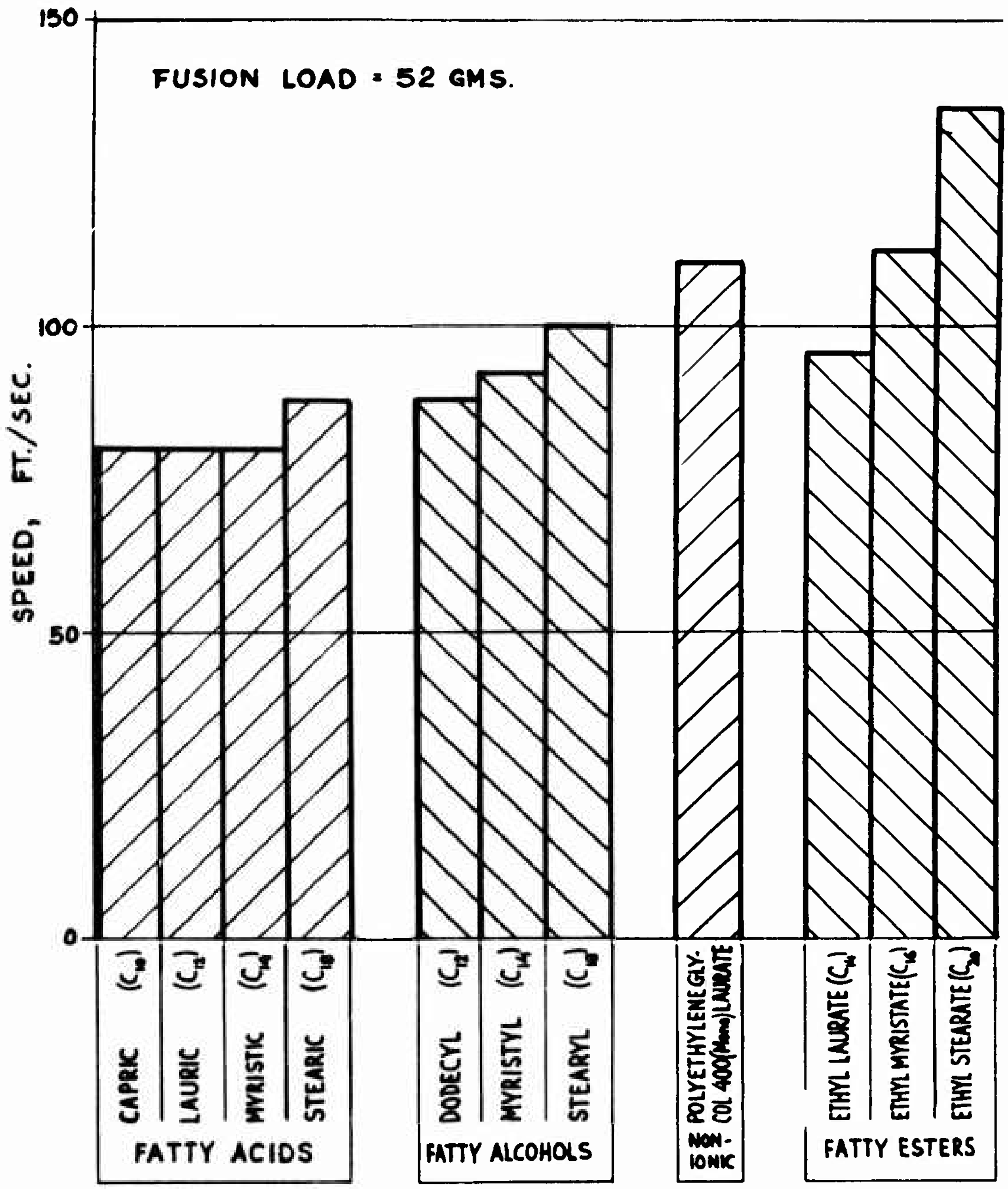


FIGURE 21. THE EFFECT OF CHEMICAL NATURE ON SPEED ATTAINED BY SLIDING PARACHUTE CLOTH AND LUBRICATED LINE AT CONSTANT FUSION LOAD.